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Saving Salmon with Fishwheels: A Bioeconomic Analysis

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ABSTRACT

The restoration of depleted wild salmon stocks in the Northwestern United States could be advanced with the re-introduction of in-river fixed gear techniques such as fishwheels, which offer substantial economic, biological, and stock assessment advantages. A dynamic simulation model demonstrates that fishwheels could reduce costs and increase net economic benefits to commercial fishers by a factor of five, and that the potentially adverse income and employment consequences that often accompany policy or technological changes can be avoided with appropriate and sequenced policy implementation. Indeed, the analysis demonstrates the feasibility of a transition path to sustainable salmon management that makes current commercial fishers better off economically, while at the same time restoring depleted wild salmon stocks. In addition, the reintroduction of fishwheels could help mitigate recent conflicts between the United States and Canada over salmon harvest allocations.

I. THE PROBLEM

The seven native salmon species in the northwestern United States have disappeared from about 40 percent of their historic breeding ranges during this century[1] and the size of the remaining wild stocks has been severely reduced. According to a recent survey, two hundred and fourteen stocks are at high to moderate risk of extinction.[2] In addition, annual returns of salmon to the Columbia River Basin have decreased from an estimated 12-16 million fish before the 1930s to 2.5 million fish in the 1980s, including those produced in hatcheries. While catch rates in some commercial

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1. Charles Huntington, Et Al., *A Survey of Healthy Native Stocks of Anadromous Salmonids in the Pacific Northwest and California*, FISHERIES, Mar. 1996 at 6; COMMITTEE ON PROTECTION & MANAGEMENT OF PACIFIC NORTHWEST ANADROMOUS SALMON, NAT'L RESEARCH COUNCIL, UPSTREAM: SALMON AND SOCIETY IN THE PACIFIC NORTHWEST (1996) [hereinafter COMMITTEE] at 1.

2. Willa Nehlsen, Et Al., *Pacific Salmon at the Crossroads: Stocks at Risk from California, Oregon, Idaho, and Washington*, FISHERIES, Mar.-Apr. 1991, at 4.

fisheries have not declined significantly, most runs that appear plentiful today are composed largely of fish produced in hatcheries. Depletion of native salmon has led to extended restrictions or outright bans on recreational and commercial fishing for several species, and several stocks have been designated as endangered or threatened under the provisions of the federal Endangered Species Act (ESA).

The decline of salmon in the Pacific Northwest has resulted from numerous interacting activities, such as agriculture, forestry, grazing, industrial activities, urbanization, dams, interactions between wild and hatchery salmon, and fishing. Salmon are particularly vulnerable to this wide range of human influences because of their anadromous life cycle whereby they spawn in freshwater, migrate to sea, and return to their natal streams several years later to reproduce and subsequently die.

Of these factors contributing to the decline of salmon, the present analysis focuses primarily on two; the role of commercial harvesting and the reliance on hatchery-reared fish. Salmon have long been important economically to commercial and sport fishers, to Indian treaty fishers, and to the communities that depend directly and indirectly on those fishing activities. They are also of cultural and symbolic importance in the Pacific Northwest, where a high "non-use" or "existence" value is placed on maintaining healthy native salmon stocks for reasons unrelated to the direct benefits from harvesting, selling or consuming the fish.[3] While commercial harvest levels in some areas have held steady into the early 1990s—in part through increased hatchery production—both commercial and sport fisheries have suffered disruptions beginning in 1994 by widespread harvest bans put in place to protect several native stocks at risk of extinction as called for under the ESA.

Even prior to these recent restrictions, the commercial salmon fisheries in Washington and Oregon suffered low net economic benefits due to the excessive size of fishing fleets and low harvest per vessel which have given rise to a very inefficient fishing economy. For example, estimates of the net economic value of commercial salmon fisheries in Washington state in the mid-1980s were negative in all regions for troll fisheries, and negative in three of five zones for gill net fisheries.[4] Fleet sizes continue to be too large for current stocks due in part to the continued decline in stock levels caused by habitat loss and other degradation of freshwater environments, including spawning grounds. Lower stocks have also resulted from poor

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3. Darryll Olsen, Et Al., *Existence and Sport Values for Doubling the Size of Columbia River Basin Salmon and Steelhead Runs*, 2 RIVERS 44, 52 (1991).

4. ICF TECHNOLOGY, INC., ECONOMIC IMPACTS AND NET ECONOMIC VALUES ASSOCIATED WITH NON-INDIAN SALMON AND STURGEON FISHERIES (1988). Appendix A.

ocean survival rates in recent years, attributable to changes in El-Niño ocean conditions in the Pacific.[5]

The plight of commercial fishing has only worsened in the 1990s with the widespread restrictions and closures of many of these fisheries. Despite widespread use of "limited entry" permitting systems to restrict the total catch, restrictions on the number of boats and types of equipment have not been successful in adequately reducing the degree of overcapitalization of the fleets, in large part because of constant pressures to allow excessive harvesting.

Hatcheries have been operated for more than a century to mitigate the effects of dams and other human activity and to replace declining natural fish populations. As a result, more than two-thirds of the salmon populations in the Pacific Northwest now consist of artificially reared hatchery fish.[6] For many years people did not recognize the potential for hatchery fish to affect wild fish, but it is now clear that these fish have had substantial adverse demographic, ecological, and genetic effects on native fish populations. Artificially reared salmon are behaviorally, physiologically, and anatomically inferior to wild salmon according to many biologists.[7] Hatchery salmon have reduced the genetic diversity within and between salmon populations, increased the adverse effects of competition between mixed-population fisheries on depletion of native populations, altered fish behavior, and caused ecological problems by eliminating the nutritive contributions of carcasses of naturally spawning salmon from streams. Furthermore, hatchery fish compete directly with native stocks for in-stream, estuarine, and ocean resources; they are increasingly recognized as reducing survival in wild salmon and reducing average fish size presumably as a result of competition for food between wild and hatchery fish.[8]

In addition, because wild and hatchery salmon are intermixed and cannot be distinguished until they are caught, the presence of large numbers of hatchery-reared salmon contributes to the pressures to permit salmon harvests above biologically sustainable levels on the wild fish when both are harvested in "mixed stocks." To protect the genetic diversity and

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5. El-Niño refers to the periodic shifts in currents and atmospheric circulation over the Pacific Ocean. In El-Niño years, the lack of cold water upwelling along the northwestern coast of North America reduces the nutrient supply available to salmon and thus lowers ocean survival rates.

6. *See* COMMITTEE, *supra*, note 1, at 302-23.

7. Ray J. White, Et Al., *Better Roles for Fish Stocking in Aquatic Resource Management*, 15 AMERICAN FISHERIES SOCIETY SYMPOSIUM 527 (1995); Gary K. Meffe, *Techno-Arrogance and Halfway Technologies: Salmon Hatcheries on the Pacific Coast of North America*, 6 CONSERVATION BIOLOGY 350, 352 (1992).

8. *See* COMMITTEE, *supra*, note 1, at 313-14.

ecological productivity of naturally spawning salmon, biologists have recommended precautions that include "an overall decrease in hatchery-fish production and—over the short term—in fishing opportunities."[9]

II. IDENTIFYING A POTENTIAL SOLUTION

Dilemmas of this kind, where multiple and conflicting private interests and public goals create obstacles for social change, are common. In this case, the long-run goal of sustaining native salmon populations is in conflict with the short-run exigencies of providing commercial fishers and their communities with harvest levels sufficient to sustain and improve their livelihoods. Although reducing the number of artificially reared salmon would benefit wild salmon populations, it would cause severe economic hardship in the short run on commercial and sport fishing industries and the communities in which they operate. Given the numerous and complex causes of the decline in wild salmon populations, implementing more efficient and sustainable salmon management policies will require considerable effort and expense, and will likely face enormous obstacles from specific interest groups. Indeed, past efforts to "buy out" or otherwise reduce existing commercial fishing effort in order to lower the allowed catch have failed to achieve adequate reductions is harvest relative to the available stocks.

How, then, can a transition be made to a more economic and biologically sustainable path? In the recent literature on "sustainable development," the notion of a "win-win" opportunity has come to refer to policies or projects that promise both economic and environmental benefit rather than trading off one for the other.[10] Most examples of these kinds of "win-win" opportunities involve the potential benefits from eliminating inefficiencies that already exist, for example where existing price distortions such as subsidies on energy, water, or fertilizers have created high demand, inefficient use, and serious pollution problems. Thus, eliminating these distorting policies can create economic as well as environmental improvements.

In the context of salmon, one technical "innovation," the reintroduction of the fishwheel for commercial salmon fishing in the Pacific Northwest, is also an example of a "win-win" opportunity. In this case the existing inefficiency takes the form of an outdated prohibition on the use of a mostly forgotten technology that appears to offer at least a partial solution to the goal of protecting the commercial fishing industry while at the same

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9. *See* COMMITTEE, *supra*, note 1, at 12.

10. WORLD BANK, DEVELOPMENT AND ENVIRONMENT: WORLD DEVELOPMENT REPORT (1992) at 1.

time reducing dependency on hatcheries. The fishwheel, a "fixed-gear" harvest technology (as opposed to floating harvest techniques from boats), is a semi-submerged waterwheel that is propelled slowly by a river's current. As the wheel rotates, netted baskets scoop up fish as they swim under the wheel and lift them out of the river. As the fish are lifted up by the rotation of the wheel, they slide gently out of the basket and into a holding tank.

Fishwheels are not a new invention. Historically, they were employed in the region, especially on the Columbia River, with great success. They were banned, however, in the 1920s and 1930s in Oregon and Washington in part because they were so efficient at harvesting salmon that fears were raised that they threatened fishing jobs and the future of the salmon runs. Crude versions of this technology are used on the Yukon River in Alaska, and modern versions have been designed and used recently on the Nass River in British Columbia.

Fishwheels have three distinct advantages over current harvesting techniques such as gill netting, purse seining, or trolling.[11] First, they are a much lower-cost technology for harvesting salmon. Second, because the fish are caught unharmed, they can be selectively released to achieve differential catch rates for different species, and in the case of marked hatchery fish, or different stocks, species-selective harvesting allows at-risk species to be returned to the river unharmed.[12] Third, because stationary fishwheels will tend to catch a fairly constant proportion of the annual returning salmon population, fishwheels can provide a relatively accurate, and hence potentially valuable, stock assessment tool for fishery managers.

A complete or near-complete conversion to fishwheels is not feasible because the efficacy of the apparatus depends on appropriate depth, width, velocity, and turbidity of the river.[13] Fishwheels have been used successfully on large systems in the Pacific Northwest including the Columbia, Fraser, Skeena, and Nass rivers, and in Alaska on the Yukon. Many of the historically successful fishwheel sites on the Columbia have since been eliminated by the hydroelectric dams that have transformed the

11. Gill netting and purse seining refer to two different kinds of boat-based net harvesting techniques used in open waters to catch salmon. Trollers use multiple long lines with lures or bait to attract salmon similar to sport fishing techniques.

12. The underlying assumption here is that species-specific or wild stock restrictions on harvesting regulations can be enforced. Currently commercial and sport fisheries in the region appear to be relatively effectively enforced in this way with a wide range of species-specific and point-of-catch restrictions.

13. *See* Michael R. Link & Karl K. English, 1996. The 1993 Fishwheel Project on the Nass River and an evaluation of fishwheels as an in-season management and stock assessment tool for the Nass River. Canadian Technical Report of Fisheries and Aquatic Sciences, 2130.

mainstem of the Columbia into a series of slackwater reservoirs.[14] Nevertheless, other kinds of fixed gear such as fishtraps or weirs[15] may have potential in locations that prove less amenable to fishwheels.

In the analysis below, we examine the economic, biological, and stock management benefits expected with fishwheels in the Pacific Northwest. Specifically the analysis examines the feasibility of a shift toward fishwheels, guided by specific policy and institutional changes, that would restore wild fish and reduce reliance on hatcheries while at the same time protecting the incomes of current commercial fishers. The study concludes in the affirmative: fishwheels offer the possibility of reconciling the competing goals of protecting the short-run interests of fishing families and preserving the long-run sustainability of wild salmon runs.

The remainder of the paper is organized as follows. In section III the economics of alternative harvest technologies are described and incorporated into a bioeconomic simulation model for comparing alternative harvest technologies. Section IV describes the results of a comparative analysis of both deterministic and stochastic models. In section V, model simulations are used to verify the feasibility of a transition path to sustainable salmon management. Some concluding comments, presented in section VI, cite additional reasons why the proposed changes might facilitate more sustainable management of salmon in the long run.

III. A BIOECONOMIC SIMULATION MODEL FOR SALMON

In this section a bioeconomic model of a salmon population is developed that is representative of the current economic and biological realities in Washington State. The economic comparisons for commercial harvesting focus on the two most important commercial net harvest techniques in the Pacific Northwest, gillnets and purse seines. For each of these, estimates of input requirements, costs, and productivity are based on fleet data and analysis for Washington State where these two techniques account for about 90 percent of the commercial salmon fishery.[16] Prices are adjusted to 1996 levels where appropriate. Statewide averages for costs and revenues are used for comparisons between these two net-gear harvesting technologies and the alternative fishwheel technology. Cost and productivity estimates for fishwheels were taken from the operations of modern

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14. *See* IVAN J. DONALDSON & FREDERICK K. CRAMER, FISHWHEELS OF THE COLUMBIA (1971).

15. Weirs are small dams or other blockages in streams below which salmon will congregate in search of a passage. Fish traps are submerged or semi-submerged tanks that salmon can enter easily, but from which they will be unable to escape.

16. ICF TECHNOLOGY, INC., *supra* note 4.

technology models designed and operated by LGL Limited for the Nisga'a Tribal Council on the Nass River in British Columbia, Canada.[17]

Table 1 presents cost, revenue and productivity estimates for these three harvest technologies. The figures show that purse seiners have higher fixed and variable costs than either gill netters or fishwheels at comparable harvest levels that could be expected with each type of gear.[18] Gill netters have fixed costs similar to fishwheels, but their harvest rates are much lower even after adjusting the assumed number of trips per vessel from the actual average of 2.69 to a more favorable range of 15-20. The catch per gill net boat leaves their average cost per fish higher than fishwheels primarily due to higher variable costs.[19]

An economic model for a representative fishery in the region is specified on the assumptions shown at the bottom of Table 1. The harvest production function is

$$H = qES \quad [1]$$

where H is harvest, E is effort in number of trips made by vessels (or days of fishwheel operation), S is the fish population or stock, and q is the "catchability" coefficient. Fleet size and the catchability coefficient are chosen to calibrate the model so that harvest per vessel, harvest per trip, revenue and expenditure rates correspond to observed values in Washington State. Given those parameters, harvest per unit of effort (trips by vessels) will vary endogenously in proportion with the stock S.

Next, the economic characteristics of these harvesting techniques are integrated with a dynamic fisheries population model. Based on a simple Beverton-Holt functional form—one of several well-known fisheries population models—this model describes the major life-stages for coho salmon (*Oncorhynchus kisutch*), emphasizing the density dependent survival

17. Michael Link, Biologist, LGL Limited, personal telephone interview; Michael Link and Karl K. English, 1996, *supra* note 13. The 1993 Fishwheel Project on the Nass River and an evaluation of fishwheels as an in-season management and stock assessment tool; Michael Link, Et al., *The 1992 Fishwheel Project on the Nass River and an evaluation of fishwheels as an in-season management and stock assessment tool for the Nass River*, Canadian Manuscript Report of Fisheries and Aquatic Sciences, 2372.

18. Fishwheels are assumed to catch 3,000-5,000 fish per wheel, although higher rates are possible. The productivity of a fishwheel will depend on the characteristics of the stream at the point where the fishwheel is installed. Historically, large variations in productivity were experienced on the Columbia River.

19. Because of evidence of a large number of part-time gill netters among the fleet, the economic comparisons modeled in the analysis below are based on assuming 15 to 20 trips per gill net boat.

from egg to smolt to adult life stages over a three year period.[20] The model used is given by

$$S_{t+2} = k_{t+1}\left(\frac{S_t}{\frac{1}{p}+\frac{1}{c}S_t}\right) - H_{t+2} \qquad [2]$$

where S_t is the number of adult spawning salmon at time t; p is the intrinsic growth rate (or density-independent survival rate) and c is the carrying capacity or maximum number of individuals that can be produced. The ocean survival rate, k, is set at 4% (consistent with empirical estimates) and is assumed to be independent of stock density (of this particular stock assumed to be small relative to oceanic capacity), and H_t is the harvest in year t.[21] Hatchery salmon are also modeled as smolts (two million per year) that are assumed to have ocean survival rates similar to wild salmon.[22]

The size of the fleet for each gear type is fixed for this analysis. For the fish population being modeled, comparisons are made between alternative fleets of 50 gill netters, 12 purse seiners, and 25 fishwheels, calibrated so that harvest rates and net economic benefits per vessel will be comparable to those observed. Since the comparative analysis below is for relatively stable trends in stocks, the possibility of entry and exit of vessel operators is omitted from the analysis.

Salmon are harvested primarily in mixed-stock groups, meaning that wild and hatchery fish are not separable by net harvesters except after harvest if hatchery-reared salmon are marked. As a result, harvest levels are chosen to achieve the desired "escapement" (the number of salmon allowed

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20. *See* RAY HILBORN & CARL J. WALTERS, QUANTITATIVE FISHERIES STOCK ASSESSMENT: CHOICE, DYNAMICS AND UNCERTAINTY (1992).

21. The following additional assumptions are made in the model: eggs per spawner are constant; the ocean survival rate of four percent in the deterministic model varies stochastically later on. Capacity, *c*, is assumed to be 6,000,000; the intrinsic growth rate, p, is 50; the number of spawners is initially 24,000 in the deterministic model, and 20,000 in the stochastic model.

22. Wild stocks will tend to have higher survival rates, although comparative analysis based on coded-wire tags has not detected differences in ocean survival between hatchery and wild salmon. However, the wild stock higher survival rate is believed to be due to low tagging data and lower recovery efforts for wild stocks. *See* M.C. Coronado, Spatial and Temporal Factors Affecting Survival of Hatchery Reared Chinook, Coho and Steelhead in the Pacific Northwest. (1995) (unpublished Ph.D. dissertation, School of Fisheries, University of Washington) (on file with author).

to return upriver to spawn) of wild salmon. Since hatchery populations do not require high escapement levels to maintain the stock size (hatchery managers typically collect about five percent of the adult population as brood stock), allowing higher rates of harvest among hatchery fish than wild fish is a desirable policy goal. Fishery managers are able to achieve a higher harvest rate as a proportion of the hatchery fish than as a proportion of the wild fish by allowing harvests to take place at times and in locations that take account of known differential spatial and temporal densities during the salmons' return to spawning grounds. Historical data indicate that with the current mix of gear and management tools, harvest rates of hatchery reared salmon can be 30 percent higher (e.g., 65 percent versus 50 percent) than wild harvest rates on average, although this will vary considerably depending on many factors, including the relative size of the wild and hatchery runs. When selective harvest is allowed in the model (implying that hatchery fish are marked so they can be identified), fishwheels are assumed to be able to harvest 95 percent of the hatchery fish because all wild fish can be released unharmed.

The deterministic version of the model assumes ocean survival to be constant and the size of the adult population to be known with certainty. A stochastic version of the model incorporates two features. First, a random variation in ocean survival, v_t, is assumed to be normally distributed as a proportion of the ocean survival rate, with mean zero and a standard deviation, $\sigma_v = 0.6$.[23] The stochastic model then has the form

$$S_{t+2} = k_{t+1}\left(\frac{S_t}{\frac{1}{p}+\frac{1}{c}S_t}\right)e^{\left(v_{t+1}-\frac{\sigma_v^2}{2}\right)} - H_{t+2} \qquad [3]$$

where the exponent's second term corrects to maintain the characteristics of a normal distribution in proportional terms.

The second aspect of the stochastic model is uncertainty. The actual stock is unknown and therefore the predicted stock, $\hat{S}$, is the basis for seasonal harvest decisions. The forecast error, w_t, is estimated to be normally distributed with zero mean and a standard deviation σ_w. Hence, the formula is

23. Stock variance estimated from time-series data for coastal and inland stocks. *See* PACIFIC FISHERY MANAGEMENT COUNCIL, REVIEW OF 1994 OCEAN SALMON FISHERIES (1995).

$$\hat{S}_{t+2} = e^{\left(w_{t+1}-\frac{\sigma_w^2}{2}\right)} k_{t+1} \left(\frac{S_t}{\frac{1}{p}+\frac{1}{c}S_t} \right) e^{\left(v_{t+1}-\frac{\sigma_v^2}{2}\right)} \quad [4]$$

The value of σ_w will vary among fishery managers, and the estimate used here is 0.20, based on subjective comparisons of ex post and ex ante stock estimates under current management practices and harvest techniques. [24] When fishwheels are employed in a fixed location, however, they will tend to capture a consistent proportion of the total stock over the course of the harvest period. This provides a more precise in-stream estimate of fish abundance that can be used to improve management. Because of this advantage, when fishwheels are used the forecast error is assumed to be standard normal with $\sigma_w = 0.05$. [25]

With these descriptions of the basic model, all three advantages of fishwheels can be represented quantitatively in the model to assess how they alter both the economics and the biology of the dynamic simulations. First, the lower cost of fishwheels should increase the net economic benefits of the fishery. Second, the ability to release nearly all wild fish unharmed makes it possible to harvest essentially all surplus hatchery fish while releasing wild salmon to maintain their escapement at desired levels. Third, the consistent harvest rates of fixed fishwheels improve stock estimation, enabling more efficient overall management of the fishery. Results of the comparative analyses are presented in the next section.

IV. COMPARATIVE ECONOMIC RESULTS

The net economic benefits of the three different harvest techniques are estimated based on simulations of both deterministic and stochastic versions of the model under the two sets of alternative assumptions: (1) a deterministic model with no uncertainty about stock; and (2) a stochastic, dynamic model representing the variability in ocean survival rates as well as the uncertainty in predicting annual stocks. The results of these simulations, shown in Table 2, indicate that for the deterministic model gill net fishers are currently uneconomic, losing about $3,000 per year, or losing

24. Estimate from Brian Edie, Fishery Manager, Washington Department of Fish & Wildlife, July 18, 1996, telephone interview.

25. Michael R. Link, The Value of an Improvement in the Precision and Accuracy of Information Used to Manage a Sockeye Salmon (*Oncorhynchus nerka*) Fishery: the Nass River Gillnet and Fishwheel Test Fishery Programs (1995) (unpublished M.A. thesis, Simon Fraser University).

$150,000 for a fleet of 50 gill net boats.[26] Purse seine boats do somewhat better, with revenues exceeding costs by about $5,700 per vessel. By contrast, the net economic benefit for fishwheels is $19,000 per unit, or $474,000 for a "fleet" of 25 fishwheels. This is an increase in net benefits of more than $400,000, or about 7 times as high as the net economic benefits if purse seines alone were used.

Of course, the most realistic set of comparisons are those from the stochastic dynamic model because it reflects the actual experience of wide year-to-year fluctuations in stocks that are difficult to predict and manage. As expected, the net revenues for all gear types are lower due to efficiency losses under uncertainty and because of the disequilibrium conditions with such large random shocks. Nevertheless, the comparisons under alternative gear types, based on 150 replicates of 30-year simulations of the stochastic model, demonstrate that the advantages of fishwheels are also very large under these realistic conditions. The net benefits per year for a fishwheel exceed those of a purse seine boat by $12,900, and they are $15,000 higher than the losses experienced by gill netters. The introduction of stochasticity into the simulations lowers the net benefits to fishwheels by a smaller proportion than for the other gear types, but by a larger absolute dollar amount. Nevertheless, the net benefits per year of using fishwheels for the entire fishery are more than 7 times as high as they would be using only purse seine boats. When wages earned directly from the commercial fishery are added to the net benefits, the difference in earnings between fishwheels and purse seines is nearly $0.5 million per year.

V. A PROPOSED TRANSITION PATH TO SUSTAINABLE SALMON MANAGEMENT

Despite the prospect of social, ecological, and economic benefits, policy changes often face opposition when they create negative effects on specific groups of individuals, or when adverse local economic impacts are anticipated. In the case of the commercial salmon fisheries of the Pacific Northwest, concern about losses of income and employment by commercial fishers, their families, and their communities, has made it extremely difficult in the past to lower harvest levels and reduce the degree of overcapitalization in these industries. This is so, in part, because short-run sacrifices are especially difficult to accept when the circumstances fishing families face are already dire. And it is nearly always the case that where

26. Negative returns to gill net fishers have been persistent for over a decade given the declining stocks and few opportunities for vessel owners to sell either their boats or their permits. Many of these vessel owners work at other jobs or fish seasonally in Alaska with a second vessel.

technological change offers increased productivity, it also carries with it the prospect of reduced employment, and this would certainly be an important concern where a reintroduction of fishwheels was under consideration.

Proposing an abrupt shift in a fishery from the current mix of fishing gear to an efficient number of fishwheels would appear to require a reduction in the number of operators and less employment. The analysis here, however, reports on an effort to ascertain whether a transition from current harvest gear to fishwheels would be possible where the levels of employment in the fishery could be maintained while at the same time improving the economic benefits for the fishers, and perhaps also allowing for a rise in the population of wild salmon.

Even if such a transition were possible, however, it is widely believed that many commercial fishers will be reluctant to abandon their vessels and the traditional boating lifestyle associated with fishing. Proposing that they give up their current way of life in exchange for the right to operate a stationary fishwheel from a river bank will undoubtedly encounter some opposition. The introduction of fishwheels during some transition period could create conflicts between newcomers and established fishing families who may regard their participation in the industry as a de facto entitlement, or property right. Nevertheless, any reduction in the number of commercial licenses under existing limited entry systems would raise the prospect of some families being forced to abandon fishing as their occupation.

In order to assess whether some of these conflicts could be avoided, a range of scenarios were simulated with the model to represent feasible transition paths that constitute both a technological innovation (reintroduction), as well as a policy or institutional innovation. The goal is to determine whether a transition to more sustainable salmon management can be designed to take advantage of the unrealized benefits from the re-introduction of the fishwheels, then to allocate those benefits in such a way, and to sequence the transition, so that no single group is made worse off, and in fact all groups benefit, during and after the transition.[27]

If the net social benefits of the change are substantial, and these benefits are captured by those who, ex ante, may resist the change, then it seems plausible that the resistance would decrease or even disappear. If fishwheel operators achieve net economic benefits much higher than existing commercial fishers, then one would expect the prospect of a

27. The proposed intervention is calculated in the spirit of the "Kaldor-Hicks" compensation criterion, but goes further by using the policy design itself to translate a potential Pareto-improvement into an actual Pareto-improvement. *See* Nicholas Kaldor, *Welfare Propositions in Economics*, 49 ECON. J. 549 (1939); J.R. Hicks, *The Foundations of Welfare Economics*, 49 ECON. J. 696 (1939).

substantial improvement in their economic well being to be sufficient to induce at least some current commercial fishers to convert from gill nets or purse seines to fishwheels. Since some may be more attached than others to the traditional forms of harvesting, a mixed fishery including fishwheels, but also some gill netters and purse seiners, may be more socially acceptable than a complete conversion to fishwheels.[28]

Currently in Washington State the shares of salmon harvested by gill netters and purse seiners are about equal. Therefore a model is specified to conform to that mix of existing harvesters. From that initial situation a feasible transition to fishwheels would shift the allocation of permits and allowable catch to one where about half of the normal harvest is allocated to fishwheels and the other half is split between the remaining gill netters and purse seiners. Specifically, the harvest is initially shared equally between 25 gill net boats and 6 purse seiners, but over the five-year transition the boat permits are reduced and fishwheel permits are increased. The number of gill net boats decreases from 25 to 8, the number of purse seiners from 6 to 5, and in their place 18 fishwheels begin operation so that 31 total "vessels" are maintained. Of course, any individual fisher may decide at any time to leave the industry by selling his or her permit to another potential operator. But allowing current commercial fishers to exchange the rights from one gear type to the other, creates the possibility that all current owner/operators could continue to fish. The total number of individuals employed in the fishery (operators and crew) actually increases from 80 to 96.

The results of this simulation are shown in figures 1- 4 from simulations over 30 years based on 150 replicates of the stochastic model. Overall, the transition path reflected in figure 1 shows a sharp rise in net economic benefits from -$50,000 per year to about $230,000 per year; the sum of net benefits and wages rises from $75,000 to nearly $400,000.

Perhaps more important from the perspective of the individual fishers themselves, the net economic benefits per vessel rise for all groups including those who continue to fish with current gear. Figures 2 and 3 indicate that those who shift from purse seines and gill nets to fishwheels increase their net annual earnings by $5,000 and $13,000, respectively. Moreover, those who continue to fish with their current gear are also made better off by about $4,000 per year in each case. These improvements are all the more valuable when they are juxtaposed with what would have occurred under a continuation of the status quo regime, indicated by the dotted lines in each figure.

28. In addition to the question of acceptability, a complete conversion to fishwheels is unlikely to be feasible because, as noted above, their efficacy is very site specific, requiring a narrowing of the river, and enough depth, velocity, and turbidity in order to perform well.

In addition, the magnitude of these benefits is sufficiently large so that harvest rates can also be reduced from 40 percent to 35 percent as the fishwheels were introduced without reducing earnings. This in turn made it possible for the population of wild salmon returning to spawn each year to rise from 20,000 to 30,000, compared to a gradual reduction in their numbers toward 15,000 under the status quo harvest regime.

The introduction of fishwheels into this fishery yields benefits of this large magnitude for several reasons. First, lower cost of fishwheel harvesting raises the net economic benefit directly for a given level of harvest. Second, because fishwheels are better able to selectively harvest salmon, a very high proportion of the hatchery reared salmon can be caught without inadvertently reducing the wild stock escapement below desired levels. And third, the improvement in stock estimation makes it possible to set harvest rates more efficiently from year to year, and this is also likely to strengthen the wild salmon populations. Over time wild stocks could recover even more, and the total harvestable number of fish would increase at the same time. Clearly, an alternative scenario could be considered that simultaneously reduced the level of hatchery production gradually while leaving commercial fishers largely unaffected.

The effect of a transition to fishwheels on economic benefits and wild stocks will vary considerably from location to location. These results are intended to illustrate the potential for increased efficiency and improved economic well-being of commercial fishers and their families, while at the same time protecting and restoring native stocks of salmonids. The benefits may be lower in some locations for a number of reasons. First, in some locations and for some salmon species the commercial potential for in-river harvesting of salmon is limited because these species display metabolic and physiological changes as soon as they enter freshwater that reduce their commercial value as a food fish. In these cases, for example for chum and pink salmon, the commercial potential for fishwheels may be small, or at least the harvested fish may sell at a discount. To allow for this possibility, the analysis above conservatively assumed a ten percent discounted price for fish caught with fishwheels. However, there is counter-evidence to suggest that salmon caught by fishwheel (especially coho and sockeye species) may actually sell for a premium above the price of fish caught in commercial net fisheries because the fish can be handled more carefully, refrigerated more quickly, and brought to market in better condition.[29]

The benefits and costs considered in the scenarios modeled above have been narrowly defined and other, additional potential benefits have not been considered explicitly in the analysis. For example, the analysis may

29. Personal communication, Michael Link, Biologist, LGL Limited, telephone interview.

understate the benefits of a transition to fishwheel harvesting to the extent that the benefits from improved sport fishing, or the non-use value of restoring native salmon stocks, are significant. Considerable evidence suggests this is so, given the many expensive and elaborate efforts being made or proposed to restore salmon populations.[30] For example, some of the measures being proposed to restore the wild salmon runs on the Columbia River would cost more than $15 million annually. And to restore salmon on a much smaller river, in 1992 Congress passed legislation clearing the way for the $110 million removal of two dams from the Elwha River in Washington. Indeed, more direct measures of the value of wild salmon include one contingent valuation survey estimating that the non-use and sport fishing benefits from a doubling of the salmon and steelhead runs on the Columbia River are $171 million annually.[31]

Costs and other considerations relevant to the reintroduction of fishwheels have not been explicitly taken account of in the analysis. For example, the selective harvesting advantage of fishwheels requires that all hatchery fish be tagged, an activity that involves significant cost, although Washington's Department of Fish and Wildlife has already begun to implement a legislative mandate to mark all hatchery coho and chinook salmon.[32] In addition, productive fishwheel operation requires choosing a location on the river with appropriate characteristics in terms of width, depth, and speed of flow, to give rise to adequate catch rates. Some rivers may not be appropriate for fishwheel operation. For example, fishwheels could not operate on the mainstem of the Columbia River where dams have eliminated nearly all free flowing river reaches.[33]

Perhaps the most significant dimension in which the analysis above may overstate the case for fishwheels is that it has ignored the very complex jurisdictional and allocation issues that would arise with any significant changes in where and when salmon are harvested. Complex and contentious issues would undoubtedly arise between offshore, mixed-stock commercial harvesters, Indian fishing rights, and the introduction or exchange of rights between net fishers and in-river fishwheel operators. Because different groups may view themselves as having de facto property rights to specific salmon stock, or to sequential priorities in terms of the seasonal migration of the salmon, harvest reallocations—even those

30. *See* COMMITTEE, *supra*, note 1.

31. Darryll Olsen, Et Al., *supra* note 3, at 51.

32. Letter from Bruce Crawford, Asst. Director of Fish Management Program, Washington Dept. of Fish & Wildlife, to William K. Jaeger, Williams College (Mar. 6, 1997) (on file with author).

33. Current use of several experimental fishwheels on the Nass River, and commercial use on the upper Yukon River in Alaska suggest that finding appropriate locations for installing fishwheels is not a major obstacle.

confronting current management decisions—raise complex issues similar to the difficult "third-party" effects that constrain transfers of water rights along a river. In addition, fishwheel operators might acquire the right to operate a fishwheel on a particular river, but may not have access to install their wheels without engaging in some form of easement contract with a local land owner.

Although these obstacles would loom large if the net economic benefits of fishwheels were marginal, since the potential net economic gains appear to be so large, it seems reasonable to hope that appropriate policies, institutions, and incentives could overcome these obstacles.

VI. CONCLUDING COMMENTS

Fishwheels were outlawed in Oregon in 1926 and in Washington in 1934 after a long and contentious political battle. The arguments included concern that these relatively cheap and efficient "dippers" threatened the future of salmon runs on the Columbia River. But the real reason at the time was an economic fight over salmon, "with the low-cost [fishwheel] production on the upper river being particularly irritating to the lower-river [gill netters]."[34] In today's circumstances, however, the fishwheel's advantages in economic efficiency and biologically-efficient management offer an opportunity for a transition from an overcapitalized, inefficient, and largely unsustainable management regime, to one that sustains the biological resource while at the same time improving the current economic well-being and future prospects of commercial fishing families.

As the model simulations demonstrate, the reintroduction of fishwheels can, in principle, be designed and implemented to distribute the large net economic benefits among those individuals who might otherwise suffer a loss of benefits resulting from changes in existing policies. A sequenced transition of this kind, where current fishers capture the substantial economic gains of improved harvesting and management efficiency, could be expected to have considerably more support among fishers and the general public than alternatives that simply reduce harvest levels.

In addition to the several direct, and estimable, benefits that a reintroduction of fishwheels would provide, fishwheels would give rise to one additional change that may be an especially important factor in promoting the long run sustainability of Pacific Northwest salmon. The decline of salmon reflects all the characteristics and symptoms of a set of complex, interacting "commons" problems due to a wide range of competing claims for harvesting fish, diverting water, disposing of waste,

34. DONALDSON & CRAMER, *supra* note 14, at 113.

and altering habitats. These conflicting interests are diverse, dispersed, and often so far removed from each other spatially and temporally that the identification of individual actions with cause and effect is virtually impossible. When fish that are returning to dozens of different streams are caught at sea, the link between a specific asset and the actions that degrade it are too far separated.

Fishwheels, however, would be operated in a location and at a time where the fish population, the catch, and the habitat and water resources that support them, are more direct, observable, and proximate. A fishwheel operator would probably take a more active interest in the protection of all the resources that contribute to a healthy fish stock in the river where his or her fishwheel is located. Unlike purse seiners, trollers, or even recreational fishers who may have little knowledge of the streams of origin for the salmon they catch, fishwheels provide a much more direct link, and hence stronger incentive, for protecting the health and integrity of the riverine and terrestrial habitats on which a specific salmon stock depends.

Evidence from a wide range of case studies and analysis of successful common-pool resource management regimes suggests that among the most important factors contributing to successful management of such resources is the direct and observable connection between the users of the resource and the consequences of their actions.[35] In the case of salmon, current institutions and interest groups are isolated from one another and removed from the resources of concern, and they have proven incapable of ensuring the long-term future of salmon.[36] It seems plausible, therefore, to suggest that a transfer of fishing rights from off-shore mixed stock fishers to operators of in-river fishwheels may alter these incentives significantly and induce a move toward institutions and policies that are more consistent with sustainable salmon management.

Indeed, the reintroduction of fishwheels may also help mitigate recent conflicts between the U.S. and Canada over salmon harvest allocations. Unlike offshore fishing boats that cannot distinguish U.S.-born from Canadian-born salmon, fishwheels catch salmon as they swim up their natal rivers so that all salmon caught in a U.S. river were born there as well. Thus, maintaining the link between resource users and the consequences of their actions can play a positive role at the international level as well. Consequently, if a significant proportion of the commercial harvest in the U.S. and Canada were caught in fishwheels, international harvest allocations would likely be less contentious. In addition, the stock assessment advantages of fishwheels could provide better information about the number of fish returning to each country's rivers, which fish stocks were

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35. *See* ELINOR OSTROM, GOVERNING THE COMMONS (1990).

36. COMMITTEE, *supra*, note 1

dwindling and why, as a more accurate basis for negotiating offshore harvest agreements.

Table 1. Economics of salmon harvest by gear type

	Gill net boat and gear	*Purse seine boat and gear*	*Fishwheels*
Vessel/unit asset value	$ 20,000	$ 65,000	$ 20,000
Fixed cost per vessel	$ 4,415	$ 21,198	$ 3,000
Annual capital cost (@ 6% of asset value)	$1,200	$ 3,900	$ 1,200
Crew size	2	5	3
Variable cost per trip[1]	$ 353	$ 1,112	$ 188 (per day)
Average catch per vessel (no. of fish)	151	4,913	2-5 % of total run
Average catch per trip	56	521	-
Average trips per vessel	15-20[2]	7 -10	20 (days)
Model base case assumptions[3]			
Number of vessels/units	50	12	25
Trips per vessel	≅23	≅10	≅20 days
Catch per vessel	≅1280	≅5,333	≅2,400-6,000
Price per fish	$8.63	$8.63	$7.77

Sources: ICF Technologies (1988). Variable and fixed costs for gill netters and purse seiners were adjusted for inflation to 1996 levels. Fish prices and asset costs were not adjusted because current fish prices have stayed at similar nominal levels; the depressed state of the fishing industry has lowered fleet values in real terms. Fishwheel data and specifications were obtained from LGL, (LGL Limited 1994) and from Michael Link of LGL Limited (personal communication).

[1] Work hours per trip are 16 for gill nets and 60 for purse seines. Fishwheel crews are assumed to work eight hours per day for 20 days and variable costs per trip are assumed not to change with the size of the catch.

[2] The actual average for gill netters of trips per vessel was 2.69 due to the skewed distribution with many part time and semi-active gill net fishers. A figure of 15-20 trips per vessel is believed to be representative of more active fishers.

[3] For a representative fishery with a harvest rate of 40 percent and total stock of about 115,000. Catch per unit effort will be a function of the concentration of the fish stock at time of harvest. To simulate conditions similar to those found in Washington State, for an assumed stock size and harvest rate, the given data on catch per vessel and trips per vessel permit the model to be calibrated by fleet size so as to be representative of the effort per catch rates actually observed. From that baseline stock and assumed productivity, trips per vessel vary in inverse proportion to changes away from the baseline stock.

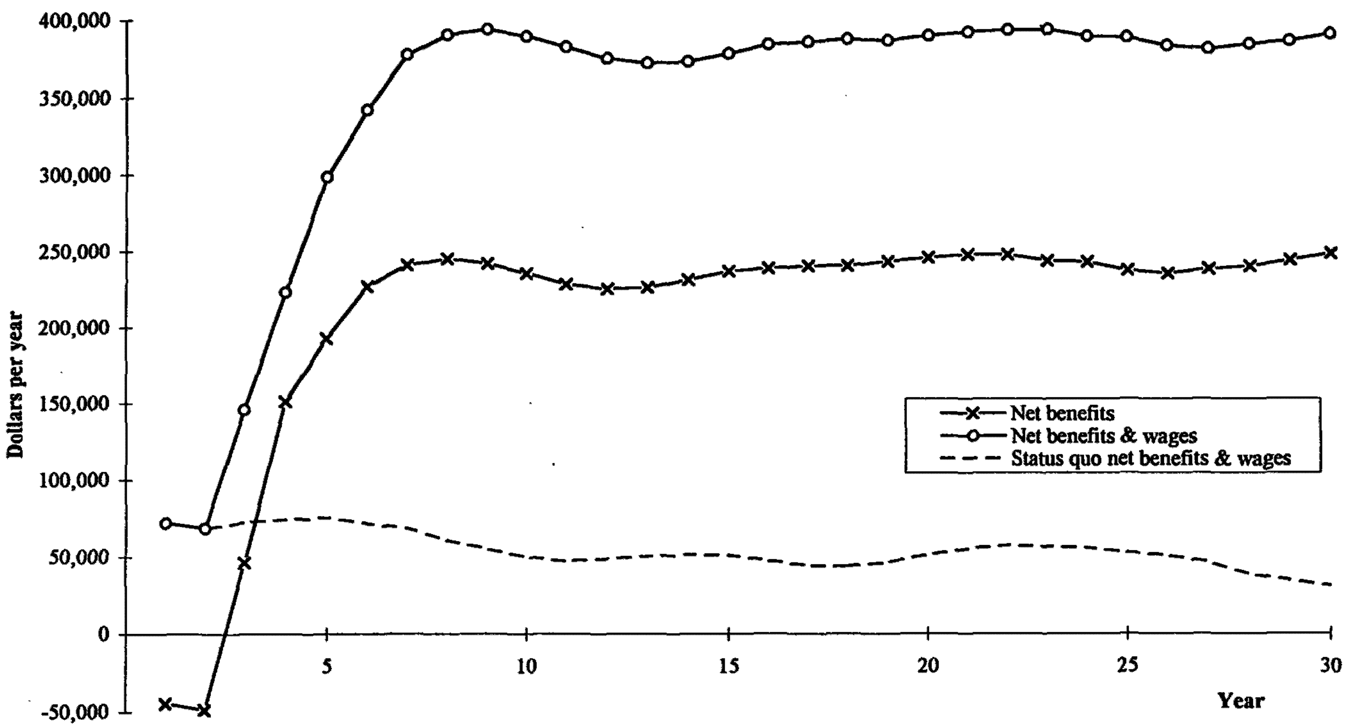
Table 2. Comparisons of net economic benefits for a salmon fishery using different harvest gear: Simulation results of a representative salmon fishery in Washington State

	Gill nets	*Purse seines*	*Fishwheels fishwheel*	*Difference: minuspurse seine*
Deterministic model				
Net benefits per vessel (or unit)	-3,000	5,700	19,000	13,300
Net benefits for a representative fishery	-150,000	68,000	474,000	406,000
Wage payments	167,000	71,000	120,000	49,000
Net benefits plus wages	27,000	139,000	594,000	455,000
Stochastic dynamic model				
Net benefits per vessel (or unit)	-3,100	4,900	17,800	12,900
Net benefits for a representative fishery	-155,000	59,000	445,000	386,000
Wage payments	145,000	61,000	134,000	73,000
Net benefits plus wages	-10,000	120,000	579,000	459,000

Notes: Simulations based on a representative model for a salmon fishery with a native stock of approximately 34,000 adult fish and hatchery production of approximately 80,000 adult fish. The harvest rate is held to 40 percent. Selective harvesting enables hatchery fish to be harvested at a higher rate of 52 percent for gill netters and purse seine fishers, 90 percent for fishwheels. Alternative fleets of 50 gill net vessels, 12 purse seines, and 25 fishwheels are considered.

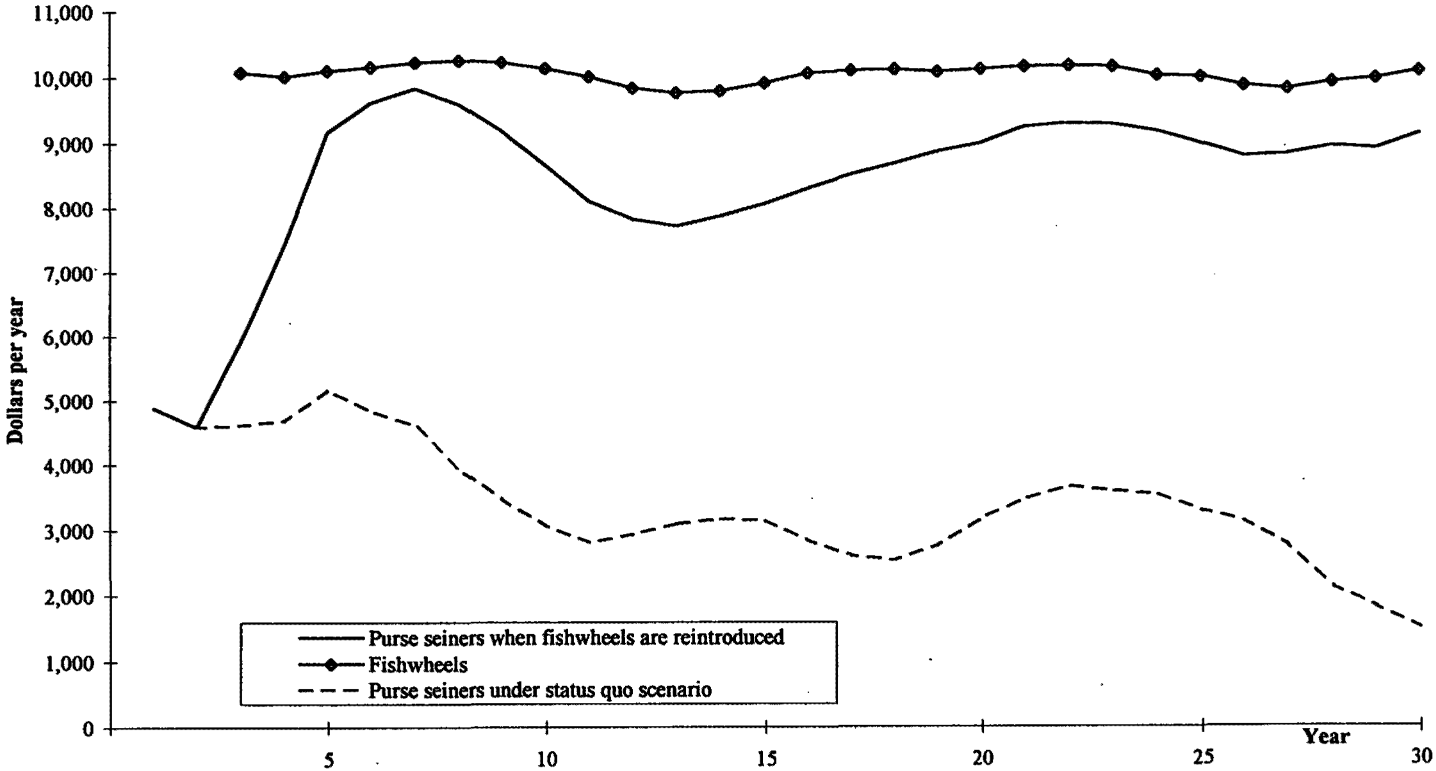
In the stochastic model, ocean survival (0.04) has a standard deviation of 60 percent. Harvest decisions are based on predicted adult populations returning to spawn. The distribution of the predicted stocks is assumed to be unbiased but with a measurement error having a standard deviation of 20 percent under gill nets or purse seines; five percent when fishwheels are employed.

Figure 1. Net economic benefits from the reintroduction of fishwheels: stochastic simulations of a representative fishery.



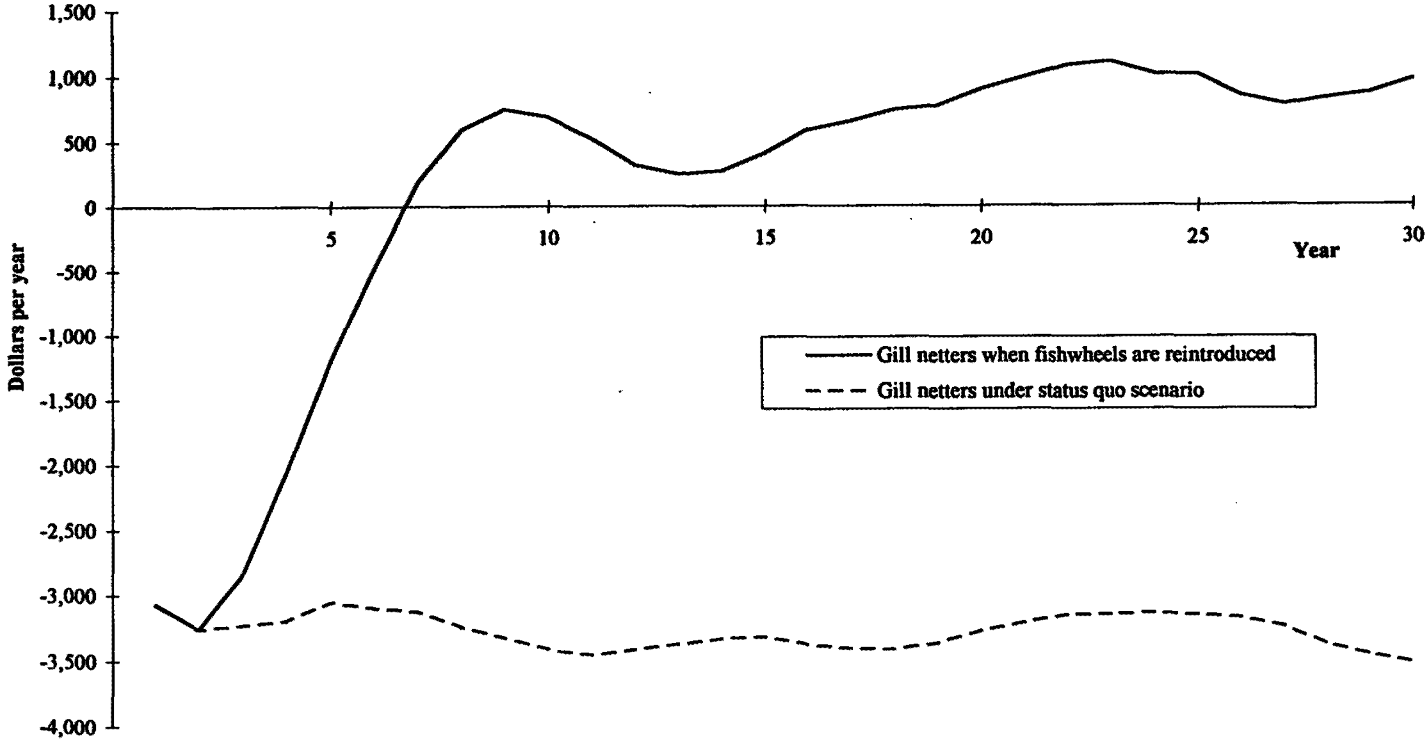
Note: Fishwheels are introduced between years 3 and 7 and are allocated half the total catch and 19 of the 31 permits. The non-fishwheel harvest allocation (and status quo allocation) is shared between the remaining gill netters and purse seiners. The harvest rate is gradually reduced from 40% to 35% as fishwheels are reintroduced. Simulation based on 150 replicates.

Figure 2. Net economic benefits per vessel/operator with the reintroduction of fishwheels: stochastic simulations of a representative fishery



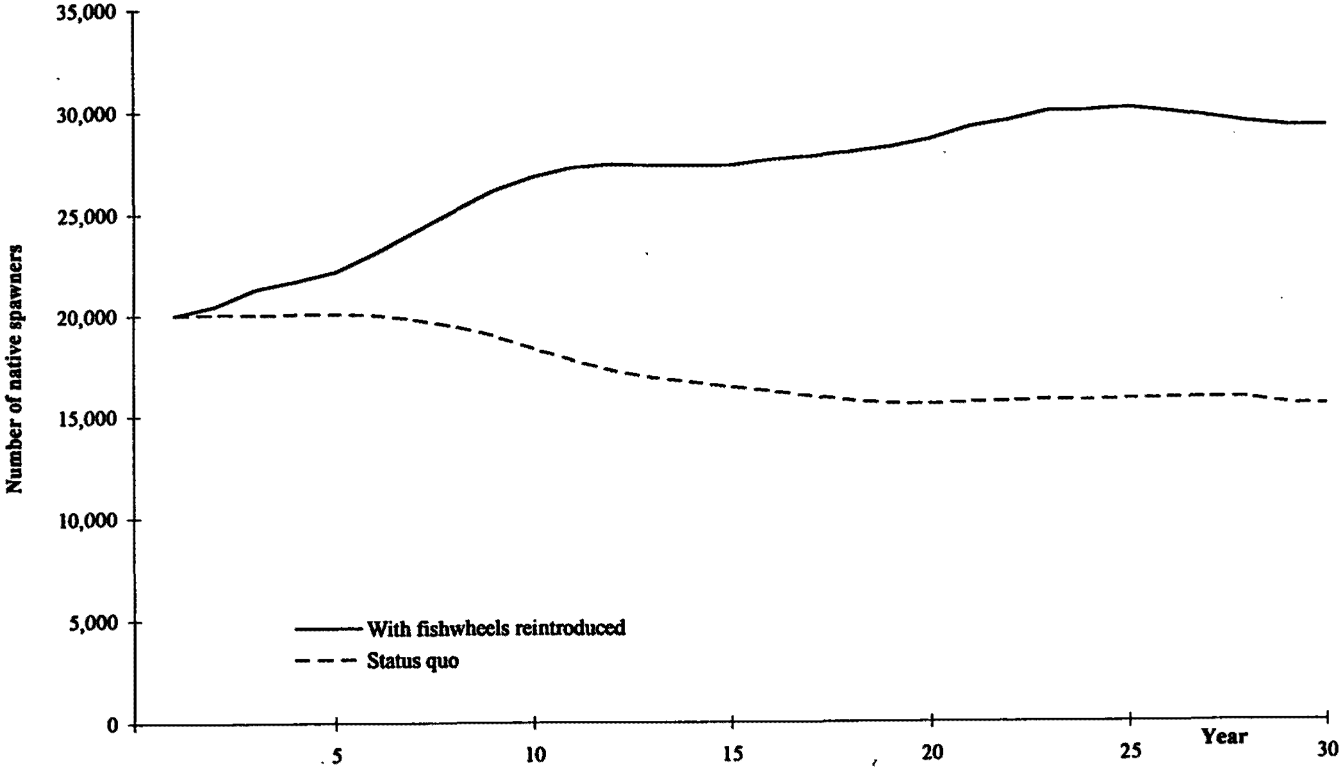
Note: Fishwheels are introduced between years 3 and 7 and are allocated half the total catch and 19 of the 31 permits. The non-fishwheel harvest allocation (and status quo allocation) is shared between the remaining gill netters and purse seiners. The harvest rate is gradually reduced from 40% to 35% as fishwheels are reintroduced. Simulation based on 150 replicates.

Figure 3. Net economic benefits for gillnetters when fishwheels are reintroduced: stochastic simulations of a representative fishery



Note: Fishwheels are introduced between years 3 and 7 and are allocated half the total catch and 19 of the 31 permits. The non-fishwheel harvest allocation (and status quo allocation) is shared between the remaining gill netters and purse seiners. The harvest rate is gradually reduced from 40% to 35% as fishwheels are reintroduced. Simulation based on 150 replicates.

Figure 4. Wild salmon escapement when fishwheels are reintroduced: stochastic simulations of a representative fishery



Note: Fishwheels are introduced between years 3 and 7 and are allocated half the total catch and 19 of the 31 permits. The non-fishwheel harvest allocation (and status quo allocation) is shared between the remaining gill netters and purse seiners. The harvest rate is gradually reduced from 40% to 35% as fishwheels are reintroduced. Simulation based on 150 replicates.