How to Improve the Management of Renewable Resources: The Case of Canada's Northern Cod Fishery

R. Quentin Grafton, Leif K. Sandal, and Stein Ivar Steinshamn

The paper examines how an easy-to-apply optimal feedback rule can be used to solve for optimal levels of exploitation of a renewable resource. Using data from Canada's northern cod fishery, the optimal feedback rule is used to derive optimal levels of exploitation for the years 1962–91 under different discount rates, alternative model specifications, and parameter assumptions. The optimal feedback rule indicates that over much of the period the fishery was economically overexploited and, given the stock development that actually took place, a harvesting moratorium should have been instituted three years earlier than when it was introduced. The results show how the use of a simple and flexible optimal rule by managers of renewable resources can generate substantial gains.

Key words: fisheries management, optimal feedback rules, renewable resources.

Many of the earth's environmental problems arise from the exploitation of renewable resources. The major causes of overexploitation include attenuated property rights, misguided policies, poverty, and simply a lack of information or understanding about the stocks and flows of resources and the timing and magnitude of environmental shocks.[1] Where the level of exploitation can be controlled, one way to help improve the management of renewable resources is to develop optimal feedback rules. As optimal feedback rules are a function of the resource stock, they can provide managers with an adaptive method of regulating resource use to achieve defined objectives and to evaluate alternative harvesting strategies.

Feedback rules have been recommended by various authors (Clark and Munro, Conrad and Clark) but have rarely been operationalized and even fewer applications exist that compare actual management with the optimal management using a feedback rule.[2] Where feedback rules do exist, they are almost always not optimal, are applied in an ad hoc fashion, and are not derived from a formal optimization model.

Using data from an important renewable resource, the northern cod fishery off the coast of Newfoundland, the paper illustrates the potential benefits of using optimal feedback rules to help achieve management objectives.[3] In particular, the results suggest that if an optimal feedback rule had been used in the fishery, very substantial economic gains could have been realized. The results are of general interest because they show how to operationalize an easy-to-use feedback rule. Moreover, the paper shows how simple models which combine the economics of harvesting, and the dynamics of the

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[1] Devlin and Grafton provide a useful introduction into the causes of environmental degradation and misuse of natural resources.

[2] Several papers consider the effects of alternative fishery management practices but do not compare actual practice with an optimal feedback rule. For example, Palsson, Lane, and Kaufmann examine alternative management strategies in the Canada's east coast fisheries and Homans and Wilen use data from the Pacific halibut fishery to model regulated open access and compare the predictions from this model with a traditional model of open access.

[3] The model applied is a generalization of a model by Sandal and Steinshamn (1997a).

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resource, can significantly improve the management of renewable resources.

The Northern Cod Fishery

Cod (*gadhus morhua*) is divided into several distinct stocks off the coast of North America. The population commonly referred to as northern cod is found in an area of over 300,000 square kilometers in the Northwest Atlantic Fisheries Organization (NAFO) regions 2J, 3K, and 3L to the east and northeast of Newfoundland. Northern cod has been commercially exploited since the sixteenth century and was traditionally caught close to the inshore in the summer. Over the century prior to the mid 1950s, total catches averaged around 200,000 tons/year and the resource was one of the most productive and valuable fisheries in the world.

Beginning in the 1950s, vessels (especially from foreign fleets) began to harvest cod in the winter when the fish aggregated far offshore. Fishing pressure increased throughout the 1960s and the total catch peaked in 1968 at over 800,000 tons, of which 85% of the total was caught by foreign vessels. Because the total harvest was far in excess of the growth in the biomass, the biomass (combined weight of cod of all ages) fell with concomitant declines in the harvest until 1978. Extended Canadian fisheries jurisdiction up to 200 nautical miles off the coast began in 1977, and reduced the foreign catch and allowed for a slow recovery in the stock. However, by the early 1980s the spawning biomass (weight of all individuals aged seven years and older) had peaked and increasing fishing mortality and relatively slow growth in several year classes led to a decline in the stock. Due to concerns over the socioeconomic impact of reduced harvests on the industry, and uncertainties over the size of the resource, decision makers were loath to reduce the total catch. Instead, the regulator instituted such strategies as a so-called "50%" rule which limited reductions in the TAC from year to year (Charles, Rivard and Maguire).[4] By 1991, the total catch was 171,000 tons, which was less than the total allowable catch, and the following year the stock collapsed. To address the crisis, the Department of Fisheries and Oceans (DFO) instituted a fishing moratorium in July 1992, which still remains in force. Despite the moratorium, as of 1997 the estimated minimum exploitable biomass was estimated at 21,000 tons, or just one percent of its level ten years earlier (Department of Fisheries and Oceans).

Several environmental factors may have contributed to the collapse of the northern cod fishery including colder than usual water temperatures, reduced salinity, increased predation by seals, and reduced food abundance (de Young and Rose, Atkinson and Bennett). Undoubtedly, exploitation of the fishery also led to a decline in the stock. Myers, Hutchings, and Barrowman suggest that overestimation of the biomass, underestimation of fishing mortality, and the ability of fishers to catch fish at low levels of abundance, coupled with high levels of discarding (especially of juveniles), were contributory factors in the collapse. Whatever the causes, the consequences have been the loss of revenue of hundreds of millions of dollars a year, thousands of jobs, and federal and provincial aid packages that to date have cost billions of dollars (Grafton).

A Bio-Economic Model of the Northern Cod Fishery

A commonly used model to represent the population dynamics for bottom-feeding fish and demersal species, such as cod, supposes density dependent growth. Density dependence implies that the smaller the size of the biomass, defined as the aggregate weight of the fish in the defined population, the greater the growth in the biomass.[5] In the absence of exploitation, surplus growth increases the biomass until it reaches a carrying capacity, defined by the environment, beyond which further growth is not possible.

[4] Charles (p. 73) observes that "scientists, managers, politicians and industry all participated in an effort to avoid disrupting the harvesting process, at the cost of failing to meet the government's declared conservation goals." The end result was a decision-making process that limited reduction in harvests. Moreover, the Minister of Fisheries was not obliged to accept the advice of Department of Fisheries and Oceans (DFO) scientists and in 1990, in the northern cod fishery, set a total catch of 197,000 tons while his own scientists recommended a level of 125,000 tons (Charles). Following the collapse of the fishery, the Fisheries Resource Conservation Council (FRCC) was established in 1993 to give independent advice to the Minister of Fisheries and help ensure the sustainability of Atlantic Canada's fisheries.

[5] For further details on the population dynamics of fish populations and modeling consult Hilborn and Walters.

Table 1. Estimated Parameters of the Growth and Inverse Demand Function

Parameter	Estimate	t-statistic	df	Function
r	0.30355	8.95	27	growth function
α	0.35865	3.92	27	growth function
a	138,569	4.48	6	inverse demand

Notes:
1. R^2 for growth function is 0.652.
2. R^2 for inverse demand function is 0.198.
3. The estimated parameter a, in the inverse demand function, was calculated using the program NLREG (4.1) which uses a nonlinear regression technique that minimizes the squared residuals for the specified (rather than a transformed) nonlinear function.
4. df = degrees of freedom.

A generalized form of density dependent growth function is defined below:

$$f(x) = rx\left(1 - \frac{x}{K}\right)^{\alpha}$$

where $f(x)$ is growth in the biomass, x is the biomass of the population, r is an intrinsic growth rate, K is the carrying capacity, and α is a parameter. If α is less (greater) than unity the growth function is skewed to the right (left). If a fishery is exploited and the biomass is less than K, then if the harvest is greater (less) than the growth defined by $f(x)$ the biomass will decrease (increase) over time.

In the case of the northern cod fishery, data is available for both the exploitable biomass (combined weight of all cod aged three years and over) and the total harvest (Rivard) for the period 1962–91.[6] Using this data, a generalized growth function can be estimated for the fishery where K is set at 3.2 million tons, a figure slightly higher than the estimated size of the biomass in 1962, and estimates of r and α can be obtained. Details of the estimated model are provided in Table 1 and the data points and predicted growth function are given in Figure 1.

The paper assumes that the fishery should be managed to maximize the discounted net revenue in the fishery over time. Such an assumption does not imply that the northern cod fishery has been managed according to this objective, but it does provide a useful benchmark to compare the model's results to past practice and show the potential benefits of using an optimal feedback rule.[7]

Net revenue ($\Pi(h, x)$) is calculated as total revenue (harvest multiplied by price of fish) less total operating costs which is assumed to be an increasing function of harvest and decreasing function of the biomass, i.e.,

$$\Pi(h, x) = p(h)h - c(h, x)$$

where h is harvest, x is the biomass, p is the inverse demand function, and c is the cost function.

To operationalize the economic component of the model, both the inverse demand $p(h)$ and cost function $c(h, x)$ need to be determined. The inverse demand function is an abstraction of the market for fish and the cost function models the relationship between harvesting costs and the stock and harvest. The actual specification of the functions is not as important as their ability to explain past movements in prices and aggregate costs and their effect on the optimal harvesting rate. When calculating the optimal feedback rule, managers should try various specifications for the functions as an input into the modeling process so as to help determine the sensitivity of the results to parameter changes. Results that are robust to changes in functional form and parameter values should give managers greater confidence in using a feedback model for management purposes.

In the case of the northern cod fishery, we assume the following inverse demand function:

$$p(h) = \frac{\bar{p}a + \underline{p}h}{a + h}$$

where $\underline{p}$ is a specified minimum price, $\bar{p}$ is a specified maximum price, and a is a parameter to be estimated. Based on observations of prices in the period 1985–91, a period for which data are available, the minimum price is set at 0.2 and the maximum price at 1.25 per kilogram. Using the price data and minimum and maximum prices, the parameter a has an estimated value of 138,570.[8]

[6] Data on harvests are available from 1959 onwards and for the biomass from 1962.

[7] See Grafton and Lane for a review of the objectives of Canadian fisheries policy.

[8] The parameter a was estimated using the program NLREG (4.1). The program uses a true nonlinear regression technique

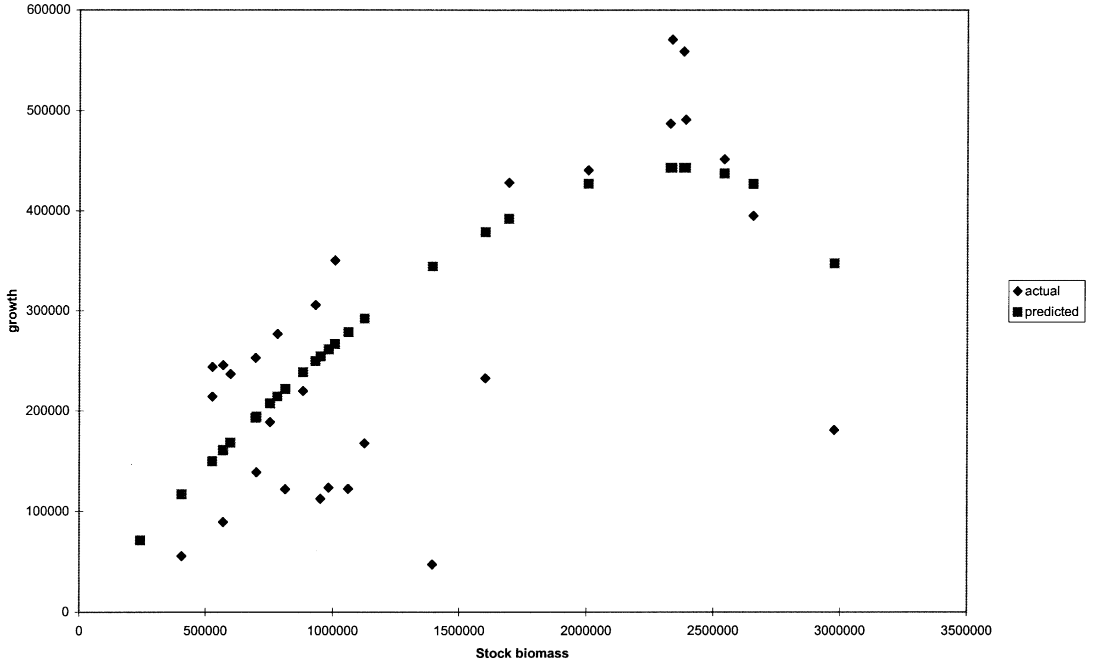

Figure 1. Actual data points and predicted growth function

Further details of the estimated parameters are provided in Table 1 while a graph of the observed and estimated prices is provided in Figure 2.

The cost function uses data supplied by the economic and commercial analysis directorate of DFO of a sample of cod fishers in NAFO regions 3K and 3L. Using the aggregate survey data for that year, an average operating cost (weighted by landings) per unit of output of \$353/ton was determined, and the following cost function derived:

$$c(h, x) = q\frac{h}{x}$$

where q is the derived cost per unit output multiplied by the exploitable biomass in 1989 and equals 200,857,000. The cost function represents an average cost per unit of harvest weighted by the ratio of the exploitable biomass in 1989 to the current level of the biomass.[9] The optimal harvest rate can be obtained using the $f(x)$, $p(h)$, and $c(h, x)$ functions and the sensitivity of the results can be calculated by varying their underlying (and uncertain) parameters.

An Optimal Feedback Rule for the Northern Cod Fishery

Many fisheries operate under some type of feedback rule such that changes in the biomass lead to changes in the harvest. In the case of the northern cod fishery, an implicit rule discouraged any changes in the TAC during a fishing season (Charles). Moreover, reductions in the TAC were constrained by a so-called 50% rule that set the next year's fishing harvesting mortality at a value halfway between the current fishing mortality and the reference point, $F_{0.1}$ (Rivard and Maguire). Such ad hoc management rules, designed to reduce the socioeconomic impact of reductions in the TAC, are not in any sense optimal feedback rules and are not based on an optimization model.

An optimal feedback rule provides a way of comparing the net benefits associated with optimal harvests and alternative harvesting strategies, such as the 50% rule. For example, if decision makers are concerned about the consequences of reduced harvests on employment, they can compare the estimated payoffs from the optimal feedback rule with the net benefits associated with maintaining higher harvests in the short term. Moreover, an optimal feedback rule provides several advantages over traditional management approaches. First, it can provide a direct

that minimizes the squared residuals for the specified nonlinear function.

[9] The cost function is similar to that employed by Palsson, Lane, and Kaufmann.

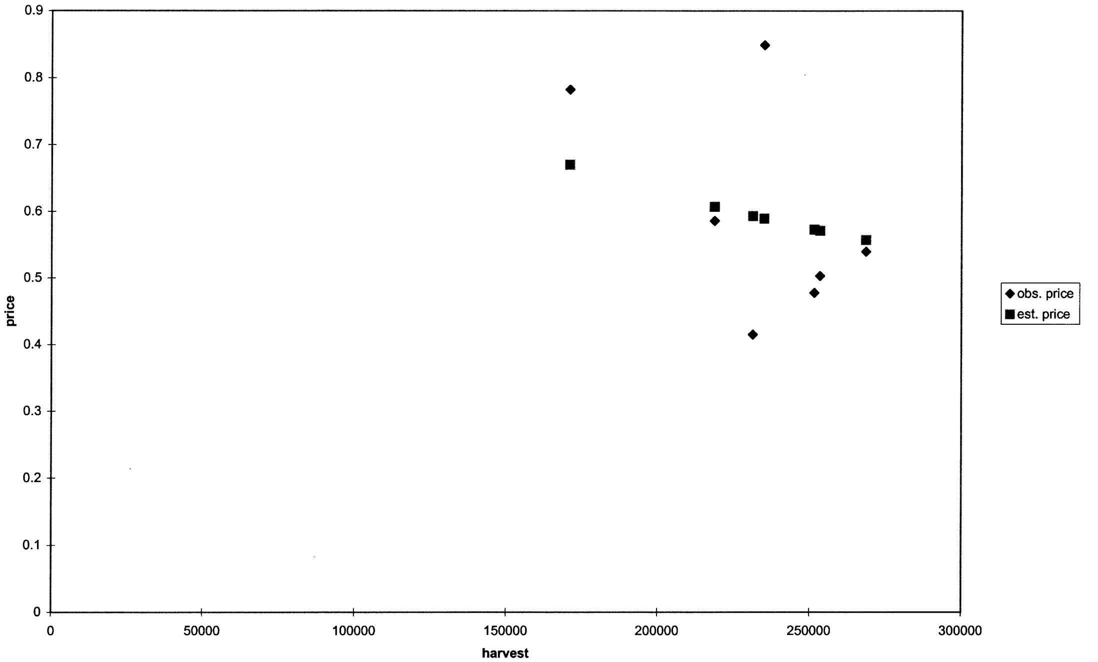

Figure 2. Estimated demand and observed prices

link between information about the resource, the optimal level of exploitation, and the optimal level of the biomass. Second, it allows managers to consider the effects of changes in the biology and economics of the fishery, as well as compare the payoffs of alternative strategies using different models and parameter values. Third, it requires that managers consider the current state of the stock in determining an optimal harvest rate.

The usefulness of optimal feedback rules is not that they capture all the intricacies of the environment or population dynamics, which is simply not possible, but that they provide a useful and simple-to-use tool to help determine optimal harvests. Moreover, an optimal feedback rule can *explicitly* consider the effects of uncertainty by testing for the effects of changes in models and parameters and allows managers to adjust the rate of exploitation to changes in the biomass. In other words, an optimal feedback rule is a form of adaptive management (Hilborn and Walters) which complements rather than substitutes for existing fisheries models.

When applying an optimal feedback rule, other models and stock assessment procedures are still required to help measure the current (and possibly future) levels of the stock or biomass. The optimal feedback rule simply uses an updated measure of the current level of the biomass every period to determine the optimal harvesting rate in the current period. Thus, the biological and economic models used in the optimal feedback rule are *not* required to predict future harvests or levels of the biomass but, instead, are used to determine a harvesting rate today that will maximize a specified objective function. In turn, the payoffs from the optimal feedback rule may be compared to alternative harvesting strategies that decision makers may wish to consider.[10]

A schema of how an optimal feedback rule may be applied in a fishery is presented in Figure 3. The figure suggests that the use of an optimal feedback rule is particularly well suited to resources, such as the northern cod fishery, where management regularly updates its estimates of the biomass and uses these estimates to determine the total harvest. Moreover, by changing the parameters and underlying models used to derive the feedback rule, managers can determine the sensitivity of the results and examine a multiplicity of scenarios about the fishery.

[10] Thus an optimal feedback rule provides a way to help address the problem that "socioeconomic considerations, long recognized as important factors in fisheries management, have usually been left to the political decision makers and often appear to be in opposition to biological advice. Further no integrated decision-making framework exists to review and analyze socioeconomic or operational considerations, along with biological advice" Grafton and Lane (pp. 141–142).

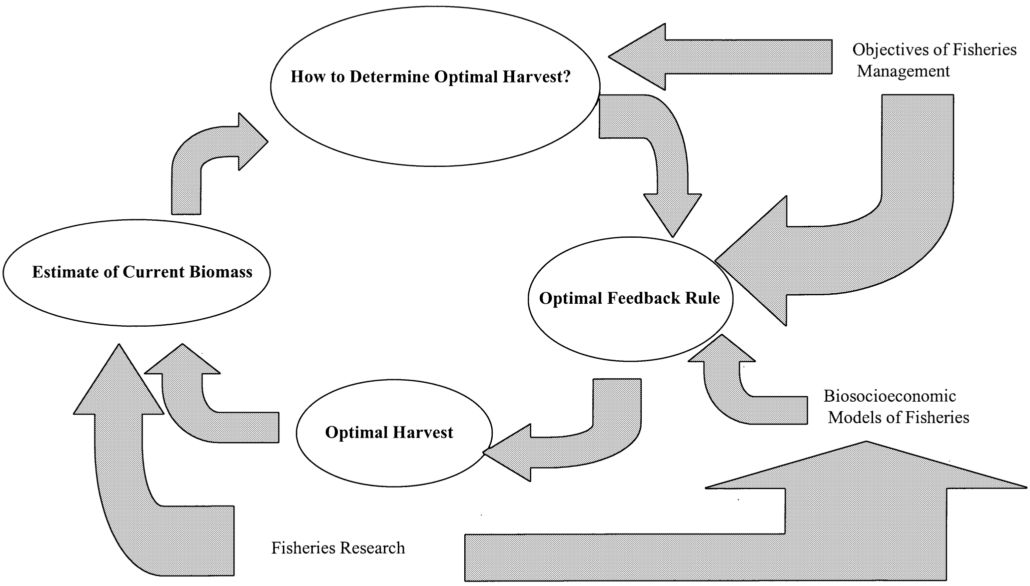

Figure 3. Use of an optimal feedback rule in fisheries management

Derivation of the Feedback Rule

If the fishery is managed to maximize the discounted net rents over time, the following maximization problem must be solved.

$$\max_h \int_0^\infty e^{-\delta t}\Pi(h, x)dt$$

subject to

$$(1) \quad \dot{x} = f(x) - h$$

where dots are used to denote time derivatives. The current value Hamiltonian for this problem is

$$(2) \quad H = \Pi(h, x) + m[f(x) - h]$$

where m is the costate variable. The first-order conditions for an optimum are[11]

$$H_h = 0$$

$$(3) \quad \dot{m} = \delta m - H_x.$$

From the first-order conditions it follows that $\dot{H} = \delta m\dot{x}$. An optimal feedback rule can be derived for $h(x)$, as follows, using the necessary conditions for an optimum. The maximum principle requires that $H_h = 0$, which implies $m = \Pi_h$, and which can be rewritten as $m = M(h, x)$. By inserting the expression for the costate variable (m) into (2), the current value Hamiltonian becomes a function of only h and x, i.e.,

$$(4) \quad P(h, x) = \Pi(h, x) + M(h, x)[f(x) - h].$$

Assuming that a feedback rule exists, the condition $\dot{H} = \delta m\dot{x}$ yields the following first-order differential equation:

$$(5) \quad \frac{dP}{dx} \equiv P_h h' + P_x = \delta \cdot M(h, x).$$

This equation can be solved numerically with respect to $h(x)$ in order to find the feedback rule. However, in order to solve the differential equation, the optimal steady state must be known.

Defining sustainable economic yield S as

$$S(x) \equiv \Pi(f(x), x)$$

the optimal steady state, with respect to x, is given by

$$(6) \quad S'(x) = \delta M(f(x), x).$$

Dividing (6) by δ, the steady state has the usual interpretation that the instantaneous

[11] Partial derivatives are denoted by subscripts. Thus $\frac{\partial H}{\partial h} = H_h$.

net return (right-hand side) should equal the discounted future returns (left-hand side).[12]

Using the already specified functions for $\Pi(h, x)$ and $f(x)$, the optimal harvest path as a function of x can be derived. In the case where the discount rate is zero, $\frac{dP}{dx} = 0$, and thus P is a constant and the Hamiltonian is constant. Given P, equation (4) defines h as an implicit function of x, where all other parameters are known, and which can be solved numerically. In the zero discount rate case, the constant P is determined as the maximum of the sustainable economic rent S, i.e., $P = \max S(x)$. Where the discount rate is positive, equation (5) is a highly non-linear differential equation but which can be solved numerically to derive the optimal harvest path.

The optimal harvest path (at 0 and 5% discount rates) and the growth function for the fishery are illustrated in Figure 4. Given that a negative harvest is impossible, where the optimal harvest function intersects with the x axis is a so-called limit reference point (Nakken, Sandberg, and Steinshamn). This point is where the exploitable biomass is at a low enough level such that a harvesting moratorium is bioeconomically optimal.

[12] For further discussion, see Sandal and Steinshamn (1997b).

Model Results

Using the estimates for the net revenue function and growth function, the limit reference point for the northern cod fishery is calculated to be approximately 626,000 tons at a zero discount rate, and 500,000 tons at a 5% discount rate and is decreasing in δ. At a discount rate of 25%, a harvesting moratorium is optimal whenever the exploitable biomass is below 200,000 tons. When the discount rate approaches infinity, the bioeconomic moratorium level will approach 161,000 tons—a biomass level below which *any* harvest will yield non-positive profit. By contrast, the regulator instituted a harvesting moratorium in the fishery in July 1992 when the exploitable biomass was approximately 108,000 tons (Rivard)—a biomass level so low that the moratorium was probably superfluous. In other words, if the optimal feedback rule had been used the resource would have been exploited more conservatively and much higher levels of the biomass would have been required to permit harvesting.

The results indicate that whatever ad hoc feedback rules (such as the 50% rule) were used by the regulator, such strategies were not optimal. Moreover, the payoffs from the optimal feedback rule can be compared to those associated with using alternative harvesting strategies. Thus, whatever the objec-

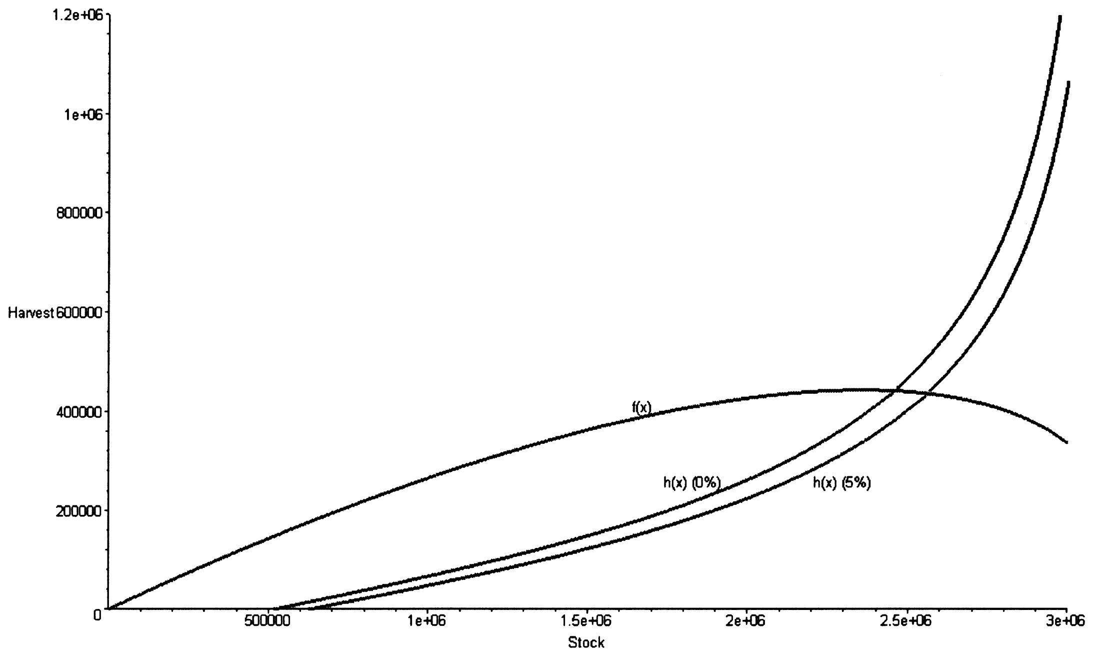

Figure 4. Growth function, and optimal harvest paths at 0 and 5% discount rates

Table 2. Actual and Optimal Harvests (000s Tons) in the Northern Cod Fishery 1962–91

Year	Exploitable Biomass	Actual Harvest	Opt. Harvest ($\bar{p} = 1.5$)	Opt. Harvest ($\bar{p} = 1.25$)
1962	2,977	503	1126	986
1963	2,655	509	497	501
1964	2,541	603	416	426
1965	2,390	545	340	352
1966	2,336	525	318	329
1967	2,382	612	336	348
1968	2,329	810	315	327
1969	2,006	754	218	226
1970	1,693	520	154	157
1971	1,601	440	138	140
1972	1,394	458	106	105
1973	983	355	53	45
1974	752	373	27	16
1975	568	288	7	0
1976	526	214	2	0
1977	526	173	2	0
1978	597	139	10	0
1979	695	167	21	8
1980	781	178	30	19
1981	882	171	42	32
1982	931	230	48	39
1983	1,007	232	57	49
1984	1,125	232	71	65
1985	1,060	231	63	56
1986	951	252	50	41
1987	812	235	34	23
1988	699	269	21	9
1989	569	253	7	0
1990	405	219	0	0
1991	242	171	0	0

Notes:
1. Opt. harvest = optimal harvest.
2. Optimal harvests are calculated assuming a zero discount rate.

tives of management (sustainability of the resource, employment, etc.), the optimal feedback rule provides a useful tool to compare the costs and benefits of alternative harvesting policies. In other words, the optimal feedback rule can be used by decision makers as a benchmark for comparison to the estimated payoffs associated with a range of policy alternatives.

Table 2 provides the actual harvest and the optimal harvests, assuming a zero discount rate, for two different values of $\bar{p}$ for the period 1962 to 1991. Figure 5 compares the actual and optimal harvesting rates for the case where $\bar{p} = 1.25$. The optimal harvest is the catch required to make the stock recover in an optimal manner to the optimal steady state of 2,558,000 tons. At the steady state, the optimal harvest rate is 436,000 tons. The results indicate that, with the exception of 1962, the actual harvest exceeded the optimal harvest over the entire thirty year period. Figure 5 illustrates clearly that the policies and feedback rules used by the regulator were not optimal over the entire period. Moreover, the results are robust to changes in the discount rate. Further, the results show that it would have been optimal to have had very low rates of exploitation in the late 1980s and, if the stock had continued to decline, it would have been desirable to implement a harvesting moratorium (given $\bar{p} = 1.25$) as early as 1989.[13]

Sensitivity Analysis

The optimal harvesting rate should be examined for its sensitivity to the specification of the $\Pi(h, x)$ and $f(x)$ functions, and their parameter values, as the models are simplifications of the underlying relationships. In terms of the inverse demand function $p(h)$,

[13] Homans and Wilen also use a harvest rule in a model of endogenous management. Their harvest rule is linear but is similar in its stock rebuilding strategy.

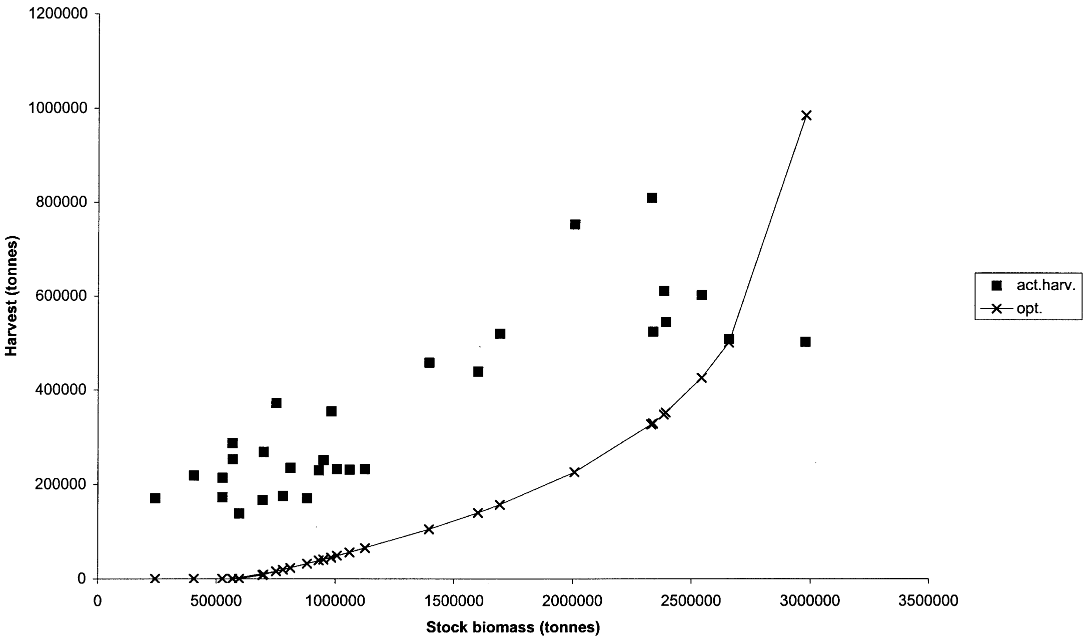

Figure 5. Actual harvest versus optimal harvest against stock when $p(\max) = 1.25$

the results do vary with $\bar{p}$, the maximum price, where a higher $\bar{p}$ requires a lower moratorium level. If the maximum price were \$1.5/kilo (with the parameter a adjusted accordingly), the limit reference point would be 506,000 tons at a zero discount rate. Thus, a 20% increase in the maximum price implies a 20% decrease in the limit reference point. Surprisingly, the results are relatively insensitive to alternative specifications for the inverse demand curve. For example, assuming a linear demand, $p(h) = a + bh$, a limit reference point of 517,000 tons is obtained at a zero discount rate while using the specification $p(h) = \underline{p} + (\overline{p} - \underline{p})e^{-ah}$ yields a 523,000 limit reference point.[14]

The results are not sensitive to changes in the cost parameter q, as a 20% increase (decrease) leads to only a 2% decrease (increase) in the limit reference point. Moreover, three different specifications for the cost function were derived, which generated very similar results in terms of the steady-state harvest and stock and the limit reference point.[15] In terms of the parameter r in the growth function, a 20% increase leads to a 10% increase (decrease) in the limit reference point. Overall, the limit reference point is relatively insensitive to changes in the parameters and the functions used.

Interpretation

The results do not imply that the optimal management of the northern cod fishery, or any other renewable resource, involves only the application of a feedback rule. Other issues, including the common-pool problem and the need to have a better understanding of the environment and measures of the stock must also be addressed if the resource is to be optimally managed. Further, the results should only be interpreted as illustrative of the possible optimal harvest rates for the northern cod fishery. For instance, the optimal harvest will depend upon a number of factors including the choice of an appropriate discount rate, measurement error in the data, and the form of the net revenue and growth functions. Thus, alternative harvest rates can also be derived depending upon the assumptions used and the values of the parameters in the model.

Despite the caveats, the potential benefits of using an optimal feedback rule in the northern cod fishery are considerable. This is true even if decision makers have multiple objectives because an optimal feedback

[14] In the linear model $a = 1.23$ and $b = 0.00000274$ while in the second model $a = 0.00000426$.

[15] These alternative specifications for the cost function and the resulting limit reference points, steady state harvest, and steady state stock are available from the authors upon request.

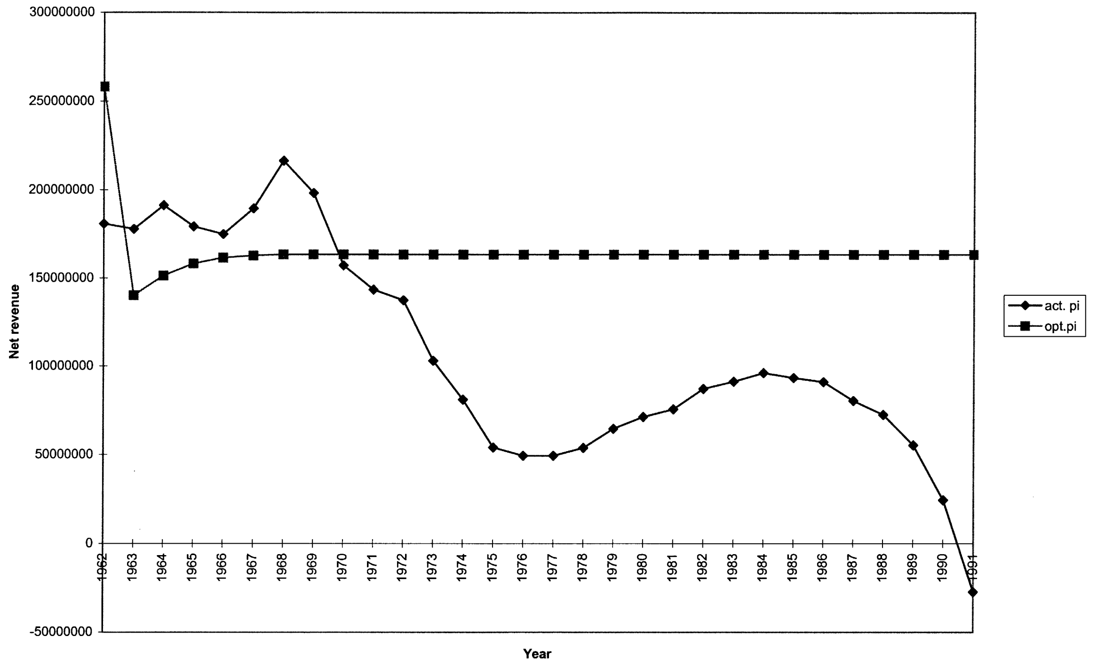

Figure 6. Actual and optimal net revenue

rule provides a ready benchmark to compare alternative policies. Moreover, the results are robust with respect to changes in model specifications and the parameters used.

Figure 6 presents the undiscounted net revenue in the fishery for the period 1962 to 1991, using the actual harvest and stock levels, and the optimal harvest and predicted stock levels. A comparison of the two net revenue streams implies that the economic benefits of an optimal feedback rule are very substantial. The results suggest that the application of a simple optimal rule from a dynamic model has the potential to significantly improve the management of renewable resources. Moreover, the data requirements to construct optimal harvesting rates are minimal, which suggests that optimal feedback rules potentially have a large number of applications.

Concluding Remarks

Some of the world's most vexing environmental problems involve the misuse of renewable resources including air pollution, overexploitation of fisheries, and depletion of water supplies and aquifers. Where there is active management of renewable resources, yields and harvests often exceed what is economically desirable. An alternative to current practice is to use an optimal feedback rule, based on a formal optimization model, to examine alternative policies and optimally adjust the rate of exploitation to changes in the resource stock. An optimal feedback rule is a form of adaptive management that complements existing management strategies and uses an updated measure of the resource stock every period to determine the current optimal rate of exploitation.

Canada's northern cod fishery illustrates the potential benefits of using an optimal feedback rule to help set rates of exploitation. In this fishery, optimal harvest rates were less than actual harvests in every year but one over the period 1962–91. Further, given the stock development that actually took place, the optimal harvest suggests that a harvesting moratorium should have been instituted three years earlier than it was introduced. If the moratorium had been implemented earlier, it may have mitigated the 1992 collapse in the stock, which, in turn, has led to billions of dollars in expenditures to assist thousands of displaced fishers and unemployed fish processing workers. The results show that optimal feedback rules have the potential to significantly improve the management of renewable resources. How to apply such rules to other renewable resources is the subject of further research.

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