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Regulation of Stochastic Fisheries: A Comparison of Alternative Methods in the Pacific Halibut Fishery

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Abstract *This article considers the relative merits of ad valorem taxation, season controls, and entry limitation as methods the government may use to deal with the externality problem in the Pacific halibut fishery. This is accomplished by simulating a stochastic dynamic program that uses parameters obtained from empirical analysis of this fishery. Although we find taxation to be the preferred regulatory instrument, the efficiency gains from regulation are minor when compared with the losses associated with the demand, output, and stock uncertainty in the fishery.*

Introduction

The regulation of commercial fisheries has been extensively studied and several important conclusions have emerged. For example, it is widely recognized that taxes and marketable quotas are equivalent optimal regulatory devices under certainty, and season length controls are a suboptimal instrument, presumably utilized only because of the unpopularity of taxes and quotas with fishermen. However, when certainty is brought into the analysis these simple conclusions change. Koenig (1984a, b) has shown in this context that taxes and quotas are no longer equivalent, the choice between them depending on the relative elasticities of market supply and demand.[1] It is claimed that the elasticities exhibited by most fisheries typically make taxes the optimal choice. However, no analysis has been made of the relative merits of season controls and entry limitation schemes in an uncertain context, and because these are the regulatory methods actually used in most fisheries, a ranking of welfare losses compared with taxes would be useful for policy purposes.

By employing an extension of Koenig's model, we attempt in this study to compare taxes, season controls, and entry limitation under uncertainty in the context of the Pacific halibut fishery, one with homogeneous fishing technology and fairly reliable sources of data. We do this by simulating a stochastic dynamic program with parameters derived from empirical estimation in this and previous studies of the fishery. Our most striking results relate to the lack of effectiveness of the alternative regulatory instruments. Although we find that taxation is the preferred means of regulation for this fishery (confirming our intuition derived from the analysis under certainty), all three forms of regulation yield levels of expected net social benefits almost identical to those generated under a competitive environment. Given the costs involved in implementing and operating such schemes, it may be preferable to permit the fishery to operate competitively. The outline of the paper is as follows: The overall model is described in the first section, along with the various cases to be compared. The subsequent section is devoted to a description of the methods for deriving the parameters relevant to our particular fishery. The results of the simulation exercise are then summarized, and the final section offers conclusions.

The Model

It is appropriate to use a dynamic analysis when modeling the actions of a government dealing with the issue of regulation, since the problem is made inherently dynamic by the relatively slow population growth in most fisheries. To model the dynamics, we divide time into discrete periods (years) corresponding to a single fishing season. We then apply the techniques of dynamic programming to characterize the various policy options that are available to the authorities.

It is appropriate to begin with the aggregate production function for the fishery, given by

$$H(t) = g[X(t), \Theta(t)]E(t) = g[X(t), \Theta(t)]N(t)f[S(t), L(t)] \qquad (1)$$

where $H(t)$ = aggregate harvest during period t,
$E(t)$ = aggregate effort,
$N(t)$ = number of (identical) boats fishing,
$X(t)$ = stock size,
$S(t)$ = number of days spent fishing,
$L(t)$ = crew size,
$g[X(t), \Theta(t)] = \Theta(t)/[\Gamma - \sigma X(t)]$
= catch per unit effort (CPUE),
$\Theta(t)$ = a random variable with mean unity which introduces output uncertainty, and[2]
$f[S(t), L(t)] = kS(t)^{\alpha}L(t)^{\beta}$
= effort per boat

As usual, the aggregate harvest is represented as the product of catch per unit effect, itself a function $g[X(t), \Theta(t)]$ of the beginning-period stock and a random term, and aggregate industry effort, in turn the product of the number of boats and effort per boat.[3] Because we wish to focus on the effects of season restrictions, the latter is assumed to be a Cobb-Douglas function of crew size and season length within the maximum season of 365 days.[4] The unusual form of the $g[X(t), \Theta(t)]$ function is necessary to make the overall model tractable; it should be interpreted as an approximation to the traditional Schaefer function $g[X, \Theta] = g_0\Theta(t)X(t)$ at the level of CPUE to which the model is calibrated.

Associated with a particular catch during period t is the dollar value of benefits accruing to consumers. We assume a quadratic benefit function given by

$$B[H(t)] = [b_0 + \Omega(t)]H(t) - \frac{b_1H(t)^2}{2} \qquad (2)$$

with parameters b_0, $b_1 > 0$, and $\Omega(t)$ a random variable (with mean zero), which accounts for demand uncertainty. It follows that the (inverse) demand schedule is

$$P[H(t)] = b_0 + \Omega(t) - b_1 H(t) \tag{3}$$

where the random variable acts as a linear demand shift.

The costs of boat operation are assumed to be a combination of unavoidable interest (capital) costs and variable wage and material costs proportional to season length. Total costs per boat are thus

$$\mathrm{TC} = r + S(t)[wL(t) + m] \tag{4}$$

where w = wage per day spent fishing, per crew member,
m = material costs per boat per day spent fishing, and
r = capital cost per boat.

Finally, following Koenig, we approximate the growth equation for the fish stock by the linear function

$$X(t + 1) = \phi_0 + \phi_1[X(t) - H(t)] + \epsilon(t) \tag{5}$$

where ϕ_0 and ϕ_1 are parameters, and $\epsilon(t)$ is a random variable with mean zero.

It must be emphasized that although the particular growth, benefit, and production relationships we have specified are in some cases different from those of the traditional model, they were carefully chosen so that the dynamic programming problem characterized below will have an objective function quadratic in the fish stock. This, in turn, simplifies the analysis considerably; it is, in fact, necessary for analytic results. We also assume the three random variables (corresponding to production, demand, and growth uncertainty) are uncorrelated both inter- and intratemporally. This assumption is utilized to keep the analysis manageable.

To facilitate the presentation of our model, we first solve for the cost function, which follows from our harvest relationship. The solution to this standard cost minimization problem is given by

$$L = \frac{\beta m}{\mathrm{w}(\alpha - \beta)} \tag{6}$$

$$S = \frac{r(\alpha - \beta)}{m(1 - \alpha)} \tag{7}$$

and

$$N = \frac{[m/(\alpha - \beta)]^{\alpha-\beta} w^{\beta} [(1 - \alpha)/r]^{\alpha}}{kg(X, \Theta)H} \tag{8}$$

resulting in total industry costs of[5]

$$C[H] = \frac{[r/(1-\alpha)]^{1-\alpha}[m/(\alpha-\beta)]^{\alpha-\beta}[w/\beta]^{\beta}}{kg(X, \Theta)H} \tag{9}$$

In a first-best situation,[6] the authorities are assumed to maximize the present discounted value of expected net benefits to society, or, equivalently, the sum of consumer surplus, and resource rents. This is given by

$$V_0 = E_0\sum_{T=0}^{\infty}\{B[H(t)] - C[H(t)]\}\mu^t \tag{10}$$

where μ is the time discount factor. As is well known,[7] by applying the techniques of dynamic programming the infinite time horizon problem can be converted into one involving only current period variables.[8] Let

$$V_j[X(j)] = \max E_j\sum_{z=j}^{\infty}\{B[H(z)] - C[H(z)]\}\mu^z \tag{11}$$

then

$$Vt[X(t)] = \max_{[H(t)]} E_t\{B[H(t)] - C[H(t)] + \mu V_t + {}_1[X(t+1)]\} \tag{12}$$

and it is straightforword to show that the solution to this recursive relationship is

$$V_t[X(t)] = e_0(t) + e_1(t)X(t) + \frac{e_2(t)X(t)^2}{2} \tag{13}$$

given the existence of a recursive relationship between the coefficients $e_0(t)$, $e_1(t)$, $e_2(t)$ and $e_0(t+1)$, $e_1(t+1)$, and $e_2(t+1)$.

Thus, from (5), (10), and (13), given convergence of the $e_2(t+1)$ coefficients, a policy of maximizing the present value of expected net benefits involves simply maximizing the extended net benefit function

$$\text{ENB}(H, X) = E\Bigg(B(H) - C(H) + \mu\Bigg\{e_0 + e_1[\phi_0 + \phi_0(X-H) + \epsilon] + \frac{e_2[\phi_0 + \phi_1(X-H) + \epsilon]^2}{2}\Bigg\}\Bigg) \tag{14}$$

in terms of current output.[9] e_0, e_1, and e_2 play the role of "shadow prices" in (14), representing the effects of current variables on future net benefits through their effects on the future stock defined by (5). It follows that the maximization of (14) results in the (ideal) crew size and season length as given by (6) and (7), respectively, while the optimal sizes of the fishery and harvest are given by

$$N = \frac{\Phi[(b_0 + \Omega - \mu\phi_1\{e_1 + e_2\{\phi_0 + \phi_1 X(t) + \epsilon]\}) - \Phi/g(X, \Theta)]}{g(X, \Theta)\,(b_1 + \mu e_2 \phi_1^2)} \quad (15)$$

and

$$H = \frac{(b_0 + \Omega - \mu\phi_1\{e_1 + e_2[\phi_0 + \phi_1 X(t) + \epsilon]\}) - \Phi/g(X, \Theta)}{b_1 - \mu e_2 \phi 1_2} \quad (16)$$

where

$$\Phi \equiv k^{-1}\left(\frac{r}{1-\alpha}\right)^{1-\beta}\left(\frac{m}{\alpha-\beta}\right)^{\alpha-\beta}\left(\frac{w}{\beta}\right)^{\beta} \quad (17)$$

Substitution of (16) and (17) into (14) then determine the level of expected net social benefits resulting from a first-best (full information) decision-making process.

The characterization of the optimal harvesting problem above assumes the government has perfect information when it makes decisions, along with complete control over the number of boats in the fishery, the season length, and labor use. This situation thus represents a benchmark against which to compare more realistic situations in which knowledge is imperfect: the government or individual boat owners making decisions without knowing the realized values of the random variables, and the government either having no control over the fishery, or controlling a commercial fishery only through indirect means.

The opposite case to the situation outlined above is competition in which individual boat owners, on the basis of imperfect knowledge, themselves determine the length of season and the size of the crew. In this case, because individual fishing boats cannot guarantee conservation by others even if they were to reduce their own harvesting, a risk-neutral boat owner would simply control season length and crew size to maximize expected current profits. This is equivalent to maximizing (14) with the e_i zero and the decisions being made prior to the realization of the random variables, giving first order conditions:

$$E\left[(b_0 + \Omega - b_1 H)\frac{\partial H}{\partial S}\right] = N(wL + m) \quad (18)$$

and

$$E\left[(b_0 + \Omega - b_1 H)\frac{\partial H}{\partial L}\right] = wNS \quad (19)$$

with entry continuing until expected fishery rents are driven to zero, i.e.,[10]

$$E\left[(b_0 + \Omega - b_1 H)\frac{H}{N}\right] = r + S(wL + m) \quad (20)$$

The problem associated with a competitive fishery is clear: overfishing occurs because individual boat owners do not respond to the fact that excess production in any one period will leave a smaller population to reproduce, thereby leading to smaller catches in the future.

The authorities have several policies available to them that could, at least partially, alleviate the problems associated with a competitive fishery. These include an ad valorem tax on landings, or direct government control of the season length or number of boats in the fishery.[11] We shall discuss each of these policies in turn, with the view to eventually simulating the effects of each in the Pacific halibut fishery.

In the case of certainty, it is well known that an appropriate landings tax can induce a competitive fishery to harvest optimally. However, this is no longer the case under uncertainty because the government must set the tax rate before demand, production, and stock growth are known. Under an ad valorem (landings) tax of rate τ, boats will fish and labor will be applied until the expected value of the after-tax expected private marginal product equals the marginal contribution of the factor to fishing costs, or

$$E\left[(b_0 + \Omega - b_1 H)\ (1 - \tau)\frac{\partial H}{\partial S}\right] = N(wL + m) \tag{21}$$

and

$$E\left[(b_0 + \Omega - b_1 H)\ (1 - \tau)\frac{\partial H}{\partial L}\right] = wNS \tag{22}$$

Acting as a Stackelberg leader (principal), the government will then

$$\max_{[\tau]} E\Bigg(B(H) - N[r + S(wl + m)]$$
$$+ \mu\left\{e_0 + e_1\,[\phi_0 + \phi_1(X - H) + \epsilon] + \frac{e_2[\phi_0 + \phi_1(X - H) + \epsilon]^2}{2}\right\}\Bigg) \tag{23}$$

subject to (21), (22), and

$$E\left[(b_0 + \Omega - b_1 H)(1 - \tau)\frac{H}{N}\right] - [r + S(wL + m)] = 0 \tag{24}$$

all fishery rents becoming tax revenues.

A situation such as a government boat buy-back scheme (used recently in the British Columbia salmon fishery) can be modeled in our context simply as direct government control of N while leaving S and L to be determined by boat owners in competition. In this case the government will maximize (14) with respect to N alone, S and L being determined from (18) and (19).

Finally, season length restrictions can be represented as maximization of (14) with respect to S subject to (19), whereas entry into the fishery guarantees that (20) will be satisfied.

Because the indirect methods of controlling the competitive fishery represent second-best situations, it is not possible to rank them by analytical means, in the sense of determining which produces the smallest reduction in welfare relative to the first-best situation. We are therefore led to consider a specific fishery to gain some insight into this issue. In the next section we outline the procedure followed in specifying the parameters that characterize the Pacific halibut fishery. We chose this fishery because it has been the subject of detailed study for a number of years, and hence our substantial data requirements are more likely to be satisfied.

Determination of the Model Parameters

To apply the framework to a particular fishery, parameters are required for the demand, production, and cost relationships, along with that describing the growth of the stock. By applying previous research in conjunction with our own empirical estimation, we are able to calibrate the model with reference to the Pacific halibut fishery, one with a long regulatory history and reliable sources of data.

A simple linear demand equation for this fishery was estimated in inverse form by Cook (1983) for the period 1936–1980, representing the demand in the area 2 subfishery (mainly the Canadian sector). The estimated function (with standard errors in parenthesis) is

$$\underset{(532.90)}{P = 1060.0} - \underset{(0.0098)}{0.04H} \qquad \overline{R}^2 = .77 \qquad DW = 1.62 \qquad \text{Method: OLS} \tag{25}$$

with price and catch being measured in 1961 dollars per ton and total tons of catch, respectively.[12] Taking this to represent the marginal benefit from harvesting in the area 2 fishery, our estimates of the b_0 and b_1 parameters then are 1060.0 and 0.04 respectively, and the variance of the random shift variable Ω is derived from the coefficient standard error, becoming $\text{Var}(\Omega) = 1.75 \times 10^4$.

Deriving parameter estimates for the area 2 harvest function is more difficult, and diverse sources of information are drawn upon. For the period referred to above, season controls were used to regulate the Pacific halibut fishery, and thus the equations representing this case are employed to help derive some of the parameters from time-series estimation. However, because no time series are available for per-boat costs, we utilize a 1968 cross-sectional survey of 26 representative vessels in the U.S. Pacific northwest halibut fishery to help fix the parameters α and β in the Cobb-Douglas effort function. Although (18) is not applicable when the season is controlled, (19), along with the entry condition, establishes that in long-run equilibrium the expected price equals average cost, and β is equal to the wage share of total output per boat, i.e., $\beta = wSL/(PH/N)$. Total revenue per boat was \$71,262 1968 U.S. dollars, according to the halibut survey, and gross wage costs (wages, captain's commission, and taxes) were \$41,307 on average, over the 1968 season. The β coefficient was then estimated at 0.577.[13]

The first-order conditions in the season controlled case establish equilibrium per-boat employment as a function of the controlled season length:

$$L = \frac{\beta(r + ms)}{(1 - \beta)S} \tag{26}$$

Substituting this relationship into the per-boat effort function, effort per boat becomes dependent on the season length (which is treated as an exogenous variable by the boat owners in this case), as well as capital, material, and wage costs, i.e.,

$$f^* = k\left(\frac{\beta}{1-\beta}\right)^{\alpha} S^{\alpha-\beta}\left(\frac{r+mS}{w}\right)^{\beta} \tag{27}$$

Having obtained series for r, m, w, and s, this equation is estimated in loglinear form, with β constrained to 0.577, yielding $\alpha - \beta = 0.240$, $\alpha = 0.817$, and $k = 0.0095$ (details of estimation and data are included in the appendix).

Because the total harvest per boat is specified as depending on a combination of per-boat effort and stock size, i.e., $h = g(X, \Theta)f$, it is necessary to estimate the parameters of the $g(X, \Theta)$ function, specified as $g(X, \Theta) = \Theta(\Gamma - \sigma X)^{-1}$. Although this function's unusual form is dictated by the need to make the model tractable, it should be regarded as an approximation to the traditional $g(X, \Theta) = g_0\Theta X$ Schaefer model. Our data, of course, refers to industrywide CPUE, defined as $\bar{g}(X) \equiv E\{g[X, \Theta]\} = (\Gamma - \sigma X)^{-1}$, average over all boats in the industry (Θ has a mean of unity). We determine the parameters Γ and σ by taking a first-order Taylor series approximation of our $\bar{g}(X)$ function at $\bar{X}$ (the mean of X), constraining this linear approximation to the traditional Schaefer function g_0X at $\bar{X}$. For example, the linear approximation of $\bar{g}(X)$ is $\bar{g} + \sigma\bar{g}(\bar{X})^2(X - \bar{X})$. The average industry CPUE from the traditional Schaefer function is $\bar{g}(K) = g_0X$, which equals $\bar{g}(X) = 0.043$ tons/skate at Cook's (1983) mean stock estimate of $\bar{X} = 29{,}344$ tons. Equating the linear approximation of our $\bar{g}(X)$ function to g_{0X} at $\bar{X}$ implies $\sigma = [\overline{X\bar{g}(\bar{X})}]^{-1} = 7.875 \times 10^{-7}$ and $\Gamma = 0.046$ as the function parameters. Of course, no information on the variance of Θ is obtainable from this method, so its standard error was taken to 20% of the mean, or 0.2. Subsequent sensitivity analysis showed the results qualitatively invariant with respect to this estimate.

The final set of parameters are those that characterize the stock growth equation. Equation 5 is a linear approximation to the traditional Schaefer logistic growth relationship, the stochastic nature of the model requiring the adoption of this particular approximation. However, one cannot estimate (5) directly because the stock size is unobservable, the only observable proxy being CPUE averaged over all boats in the fishery, or $\bar{g}(X)$. There are two possible ways to estimate (5), given our $\bar{g}(X)$ function. If we were to assume our $\bar{g}(X)$ function to be a correct representation of the relationships between catch and stock in the fishery, we could estimate the ϕ_0 and ϕ_1 parameters of (5) by inverting $\bar{g}(X)$ to get effort per unit catch (EPUC) as a linear function of EPUC_{t-1} and H_{t-1}. However, as previously discussed, the assumed function should be regarded as particular approximation made necessary by the model structure, not a true representation of reality in the fishery. It therefore appears more sensible to assume the traditional Schaefer CPUE function. $\bar{g}(X) = g_0X$ for purposes of estimation, which in conjunction with (5) yields

$$\text{CPUE}_t = \phi_0 g_0 + \phi_1 (\text{CPUE}_{t-1} - g_0 H_{t-1}) + g_0\epsilon \tag{28}$$

as an estimating equation. Because the lagged CPUE and harvest variables are independent of current CPUE in an econometric sense, this relation can be estimated using NLS to obtain ϕ_0, g_0, and ϕ_1. However, we have prior information on g_0 from Cook (1983), who estimated the traditional logistic growth function for the stock (using the same data over the same period). Constraining g_0 to her estimate of 0.12×10^{-5}, we obtain, $\phi_0 = 6259.863$ and $\phi_1 = 0.87216$ (details in the appendix). The growth equation error variance was determined as the square of the estimated regression standard error divided by g_0, or $(7921.84)^2$.

Model Simulation

Given the values of the model parameters, our first task is to simulate the model in the first-best case of complete governmental control of the fishery. The determination of the expected present value of net benefits in this case represents a benchmark against which to compare the other cases.

While the season length and crew size in the optimal case are specified by (6) and (7), respectively, to calculate the optimal N and H and net social benefits from (14) we require the values of the e_0, e_1, and e_2 coefficients. These are calculated at their equilibrium values by solving the implicit recursive relationships between them. For example, it is straightforward to show that there exist functions $h_0(\ )$, $h_1(\ )$, and $h_2(\ )$, such that

$$e_0(t) = h_0[e_0(t+1), e_1(t+1), e_2(t+2); \ldots \text{Parameters} \ldots]$$

$$e_1(t) = h_1[e_1(t+1), e_2(t+1); \ldots \text{Parameters} \ldots]$$

and

$$e_2(t) = h_2[e_1(t+1), e_2(t+1); \ldots \text{Parameters} \ldots] \tag{29}$$

Given this characterization, it is natural for us to utilize a fixed-point iterative process to determine the point of convergence, (e_0^*, e_1^*, e_2^*). This involves specifying the parameters that characterize the benefit, cost, and growth relationships, then invoking a fixed-point algorithm[14] to generate the actual values for e_0^*, e_1^*, and e_2^*. Once this has been accomplished, the particular values are substituted into the various first-order conditions enabling us to determine the optimal number of boats, the expected catch, and the maximum $V(X)$ given an estimated stock level. The exercise is then repeated for the various alternative cases. We report the results in Table 1.[15,16]

In the first-best situation, expected output is 7425.2 tons, with expected net social benefits of $1,544,833.00 in 1961 dollars.[17] A competitive fishery, in contrast, has expected output 4.2% higher than its optimum value, although season length and crew sizes are still at optimum cost-minimizing levels. This increase in expected output reduces expected net social benefits because social marginal costs exceed marginal benefits at the competitive equilibrium as a result of the common property externality.

an ad valorem tax on landings represents one method that can be used in an attempt to internalize the external diseconomy. However, because the tax by assumption must be set in advance of the realization of the random variables, the (social) gains associated with taxing this fishery are small when compared with a competitive situation. With our estimated parameters the optimal tax is only 0.30%, with expected output 103.5% of its first-best level. The increase in expected net social benefits is only 0.004% as compared to the competitive situation, although it is still significantly less than in the first-best situation.

Direct controls on the number of boats is a regulatory device that has been used in

Table 1
Input Use, Expected Output, and Expected Net Social Benefits under Alternative Regimes

Parameter	First-Best	Competitive Fishery	Ad Valorem Tax	Control S	Control N
τ	—	—	0.0030	—	—
S	139.89	139.89	139.89	137.68	140.67
L	4.83	4.83	4.83	4.86	4.83
N	123.63	133.50	132.56	134.69	132.57
$E(Q)$	7,425.18	7,740.41	7,686.28	7,740.17	7,721.86
ENB	1,544,833.00	1,267,247.71	1,267,306.72	1,267,172.72	1,267,267.91
CS	1,491,153.00	1,226,251.52	1,209,252.44	1,226,166.01	1,220,370.21
RENT	6,197.21	0	17,030.12	0	5,850.94
DEFNB	47,482.79	41,006.19	41,125.16	41,006.71	41,046.75

the British Columbia salmon fishery. As is to be expected, a forced reduction in the number of boats will lead to the substitution of other inputs; thus, the increase in season length to 140.67 days. Overall, we find that by controlling entry directly expected output falls by only 18.6 tons per year relative to the competitive situation, and the level of expected net social benefits only minimally exceeds that of competition. Our analysis thus seems to confirm the negative experience of British Columbia authorities with entry limitation as a regulatory tool.

Our final regulatory instrument is one of direct controls on season length in the fishery. We find that the imposed reduction in S will lead to induced increases in both boat numbers and crew size. Expected output also falls relative to competition, but again only by an insignificant amount. The conventional wisdom concerning the relative inefficiency of partial controls on effort derived from analysis of the fishery under uncertainty thus seems to be upheld under uncertainty for this fishery.

To this point, we have compared and contrasted several different situations ranging from a competitive fishery to one of complete government control. The question arises, however, as to whether the results are dependent on the values specified for the parameters. In considering this issue, it is important to remember that the values for the various parameters are not chosen arbitrarily, but are estimated in this and previous studies of the Pacific halibut fishery. It is for this reason that our concerns are muted considerably. In any case, we have completed a full sensitivity analysis of the parameters. This involves changing them one at a time, generating new values for e_0^*, e_1^*, and e_2^*, substituting them into the various first-order conditions, and finally determining the new values for the endogenous variables. Since the number of parameters exceeds 20, for the sake of brevity, we will not report our results directly. However, we do find that the results reported previously are extremely robust, in each case remaining qualitatively unaffected.

Concluding Remarks

The externality problem inherent in fisheries has long been recognized. In this article we have examined a variety of regulatory devices in the context of the Pacific halibut fishery. This particular fishery was chosen because it has been studied for many years, and hence the required data are more likely to be available. Our analysis confirms the conventional wisdom that direct controls over either the season length or the number of boats in the fishery are typically ineffective, in the sense that the level of expected net social benefits generated when either is implemented is almost identical to that under a competitive environment. As in the case of certainty, we find that an ad valorem tax on landings dominates either form of direct controls on the fishery as a regulatory instrument.

Appendix: Details of Parameter Estimation for the Effort and Stock Growth Equations

As discussed in the text, equilibrium per-boat effort in the season-controlled fishery was determined as a function of season length (S), capital cost (r), material costs (m), and wage costs (w) per day fished during the season. Defining $V = (r + mS)/w$,[18] according to our specification this function is loglinear in S and V, becoming

$$f^* = k\left(\frac{\beta}{1-\beta}\right)^{\alpha} S^{\alpha-\beta} V^{\beta} \tag{A1}$$

with k, α, and β as parameters.[19] While all three parameters could be estimated from (A1), we have a priori information on β. Equation A1 was therefore estimated with β constrained to 0.577, becoming

$$\log(f^*) - 0.577\log(V) = \underset{(29.4)}{-4.3932} + \underset{(4.83)}{0.23714}\log(S)$$

$R^2 = .647$, DW $= 1.81$, $F = 31.19$
Sample: 1930 to 1958, 1968 to 1974
Method: GLS CORC

A subsequent regression with β unconstrained confirmed the restriction as unconstrained β was not significantly different from 0.577.

The stock growth function (5) was estimated by taking catch per unit effort (CPUE) as a proxy for the stock, assuming the traditional proportional model $\overline{\text{CPUE}} = g_0 X$, with g_0 the "catch-ability coefficient" estimated by Cook (1983) as 0.12×10^{-5}. Employing a dummy variable (TROLL) to account for the effects on the stock of the recent incursion of small trollers not counted as regular members of the fishery,[20] and constraining g_0 to Cook's estimate, the hypothesized stock growth relationship is

$$\text{CPUE}_t = g_0\phi_0 + \alpha\text{TROLL} + \phi_1(\text{CPUE}_{t-1} - g_0 H_{t-1}) + u$$

where $u = g_0\epsilon$ is the error term. This was estimated as

$$\text{CPUE}_t = (0.12 \times 10^{-5})\underset{(2.67)}{(6259.86)} - \underset{(2.00)}{6.188}\ \text{TROLL}$$

$$+ \underset{(14.1)}{0.872164}[\text{CPUE}_{t-1} - (0.12 \times 10^{-5})\, H_{t-1}]$$

$\bar{R}^2 = 0.805$, Durbin's $H = 0.9013$, $F = 104.7$
Sample: 1930 to 1980

A regression with g_0 unconstrained produced a g_0 estimate of 0.26×10^{-5} but this was not found statistically different from Cook's estimate.

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Notes

1. Other relevant papers are those of Andersen (1982), Andersen and Sutinen (1984), Anderson (1986), Koenig (1985), and Yohe (1984).

2. Output uncertainty is introduced in a multiplicative fashion so as to be consistent with the literature; see, for instance, Hiebert (1978). Of course, making Γ random would have introduced output uncertainty, but in a more restrictive manner since the random disturbance would then be confined to the cost function's linear term; see Koenig (1984a).

3. In the halibut fishery effort is measured in "skate soaks" per time period. The skate is a unit of longline fishing gear representing a standard length of line with a given number of hooks that is left in the water (soaked) for a fixed length of time. The standard skate is 1800 ft of line with 100 hooks spaced at 18-ft intervals, originally representing the gear weight that could be handled by one man. Standard soak time is 12 h.

4. The traditional Schaefer function, of course, is much more restrictive, assuming $g(x) = g_0X$ and a coefficient on aggregate effort of unity, implying $\alpha = \beta = 1$. There has been considerable discussion in recent years concerning the relevance of this assumption for many fisheries. Henderson and Tugwell (1979) in a study of Canadian lobster concluded both that CPUE did not increase proportionately to stock size and that the coefficient of aggregate effort was $\alpha + \beta = 0.44$, significantly less than 2. Tsoa, et al. (1985) studying Newfoundland cod, on the other hand, found CPUE essentially proportional to population and $\alpha = \beta$, both insignificantly different from unity. We subsequently estimate $\alpha = 0.817$ and $\beta = 0.577$, so $\alpha + \beta = 1.394$.

5. This cost function is linear in the harvest rate, implying constant long-run marginal costs at the minimum of short-run average cost per boat. Although such a formulation ignores crowding effects or possible pecuniary diseconomies, (see Anderson (1982) or Cook and Copes (1987)), we feel this is a reasonable assumption to make for a relatively small fishery.

6. The term *first*Π*best* is used to describe a situation in which the government (our principal) has complete control over the fishery in that it determines the levels of all inputs, including the number of boats. When the government makes decisions it also has exact knowledge regarding the actual levels of the random variables.

7. See Chow (1975), especially Chapter 7 and 8.

8. This assumes optimal (full information) choices involving N, S, and L are made in all future time periods.

9. Time subscripts have been dropped in this and subsequent formulas to simplify the notation.

10. Although the characterization of the first-best optimum assumes that the authorities have full information when making decisions, this does not follow with the competitive, tax, season control, and entry limitation cases. For this reason, the cost function generated above cannot be used in analyzing this schemes.

11. Individual boat quotas are not analyzed because in the context of our type of harvest uncertainty it is difficult to know how they could be either modeled or actually administered.

12. Cook's original equation included the price of salmon as an explanatory variable. Because this is exogenous to our model, we have collapsed this variable at its mean value into our equation's constant. The standard error for our constant does not include the variance of salmon prices because we assume the regulatory authorities have knowledge of this variable. The coefficients have also been adjusted for the fact that Cook measured her data in pounds rather than tons.

13. The survey could not be used to estimate α because data on season length were not included. We use a time-series regression below to estimate this coefficient.

14. The Chow-Yorke algorithm (no. 555) from the ACM algorithms distribution service was used.

15. The wage (w) and material costs (m) are measured in dollars perday, whereas r represents the capital cost per boat, per year. The season length (S) is measured in days, the crew size (L) in workers per boat, and the expected output of the fishery, $E(Q)$, in tons. Finally, expected net social benefits (ENB) are measured in 1961 Canadian dollars. From the data sources mentioned previously, we find $w = 36.971$, $m = 73.047$, and $r = 7896.623$. Also, we assume $\mu = 0.05$, and generate the following values: $e_0 = 3567977.466$, $e_1 = -321.925$, and $e_2 = 0.017$.

16. In the first-best case the number of boats will be random, whereas in the other cases, this does not follow. In Table 1, we therefore report the expected size of the fleet in the first-best case and the (nonstochastic) number of boats in the remaining cases. Also, in the table, ENB corresponds to the present discounted vale of the fishery's expected net benefits to society in the various situations. CS measures the consumer surplus and RENT the economic rent accruing during the initial period of the infinite planning horizon. Finally, DEFNB refers to the present discounted value of the expected future net benefits to society, i.e., DEFNB $= \mu V_{t+1}[x(t + 1)]$.

17. This is somewhat smaller than the \$1.71 million social surplus derived by Cook and Copes (1987) in a static certainty analysis, while our optimal expected output is larger than their 9.83 million pounds (4915) tons. This difference is due to the effects of the uncertainty in our model and to the different functional forms employed.

18. To measure r (defined as $P_k(i + \delta)$ where P_k is the average value of a fishing boat, and i and δ are interest and depreciation rates) we specified i as the Canadian corporate bond rate and fixed δ at 1.7%, the value specified in the 1968 cross-section boat survey. P_k was measured in Canadian dollars as the average price of a boat in 1961 (from the boat survey) multiplied by the industry selling price index for boat building and repair in British Columbia (1961 = 100) times the Canadian exchange rate. m was similarly related to its value in the survey scaled by the British Columbia whole-sale price index. w is measured similarly using the British Columbia index of weekly earnings times one minus the unemployment rate, to get a measure of the expected opportunity wage.

19. Total effort in the fishery was obtained from annual publications by the International Pacific Halibut Commission (IPHC), available from 1929 to the present. However, the estimation period was limited by the availability of data on the number of boats in the fishery, which is necessary to calculate effort per boat (f). The number of boats in the regular fleet was published directly by the IPHC only from 1968 to 1974, although data from 1929 to 1958 were obtained from Crutchfield and Zellner (1962), who acknowledged their source as the IPHC in unpublished form. Consequently, because the ultimate data source was the same, the model was estimated as a whole from 1930 to 1958, and 1968 to 1974. A Chow test on equality of coefficients for the two samples separately had an F value of 2.11, which is not statistically significant at the 5% level, confirming the sample pooling.

20. TROLL is unity after 1966, zero previously.

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