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A Stochastic Dynamic Programming Model of Bycatch Control in Fisheries

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Abstract *This paper builds a model of fishery regulation with incidental catch or bycatch and simulates it with parameters from the Nova Scotia cod and haddock fisheries. When comparing optimal coordinated taxation with the independent taxation of each fishery separately, we find that independent taxation requires significantly higher tax rates to control the stock externality associated with competitive behaviour. Quotas are found to be suboptimal relative to any form of taxation, because of their inflexibility in the presence of uncertainty, and because they can control bycatch only indirectly.*

Keywords bycatch, externality, quota, regulation, taxation

Introduction

The externalities associated with open-access commercial fisheries are now well understood, and there is wide consensus on the need for government regulation. A number of means have been proposed to control the common property problem, but most attention to date has focused on taxes and quotas as regulatory instruments.[1] The typical analysis is limited, however, in that the interaction between species is ignored. While there can be a number of biological and technological interactions, including predator-prey relationships, the most important concerns bycatch, or the incidental catch of one species in a fishery directed towards another. This phenomenon is important when fishing gear is not selective, as with the bottom trawl.[2] With a significant bycatch regulation is clearly more difficult, in that the relevant taxes or quotas must be determined simultaneously, with possibly different policies respecting primary catch and bycatch.

The authors are indebted to two anonymous referees for their suggestions.
[1] See Anderson (1986), Androkovich and Stollery (1989), Clark (1982), Koenig (1984) and Weitzman (1974).
[2] The selectivity of fishing gear itself may be an economic decision subject to the influence of government regulators. We ignore this complication in our analysis, treating fishing gear as technologically given.

In this paper we extend previous analysis by considering the regulation of two technologically interrelated fisheries in a stochastic setting.[3] A model is first developed, then dynamic programming techniques are utilized to determine the dual optimal taxes or quotas. Using parameters derived from the cod and haddock fisheries in the Northwest Atlantic Fisheries Organization area 4X (Nova Scotia, Canada), we compare the expected net economic benefits from optimal fishery regulation of both species in a simultaneous fashion with the regulation of each fishery separately (ignoring bycatch), and with the open-access equilibrium. In the context of these fisheries, we find optimally structured taxes to improve economic welfare 11.3 percent relative to open-access, compared with a 12 per cent improvement for complete first-best control of both fisheries. Independent tax regulation (ignoring bycatch) improves welfare 10.2 per cent. Quotas, by contrast, are found in our context to be inferior to both types of taxes, and even to unregulated competitive behaviour.

The remainder of the paper is organised as follows: the next section outlines the theoretical models of competition, full-information optimum, tax and quota regulation in the interrelated fisheries. Section three describes the methods used to obtain the parameters for the simulation experiments in section four. The final section offers conclusions.

The Model

Let $X_I(t)$ and $X_{II}(t)$ represent the biomass levels of species I and II, respectively, during period t. With $e_1(t)$ representing effort for fishery one, the Schaefer fishery production function gives the primary catch (of species I by fishery one) as

$$Q_1(t) = k_1 e_1(t) X_I(t) \theta_I(t) \tag{1}$$

while the bycatch (of species II by fishery one) is given by

$$\Omega_1(t) = k_2 e_1(t) X_{II}(t) \theta_{II}(t); \tag{2}$$

where the k's are parameters and $\theta_I(t)$ and $\theta_{II}(t)$ are uncorrelated random variables with mean unity. Similarly,

$$Q_2(t) = w_2 e_2 X_{II}(t) \theta_{II}(t) \text{ and } \Omega_2(t) = w_1 e_2(t) X_I(t) \theta_I(t) \qquad (3),(4)$$

represent the primary and bycatch for fishery two. Uncertainty in the model thus takes the form of random catch rates for given stock and effort levels.

The two fish stocks are assumed to grow according to the linear functions

$$X_I(t+1) = \phi_0 + \phi_1[X_I(t) - Q_1(t) - \Omega_2(t)] \text{ and} \tag{5}$$

$$X_{II}(t+1) = \phi_2 + \phi_3[X_{II}(t) - Q_2(t) - \Omega_1(t)]. \tag{6}$$

While these can be considered as linear approximations to the traditional logistic

[3] Previous research on the by-catch problem has typically ignored the presence of uncertainty; for instance, see Anderson (1975) and Clark (1976).

functions for biomass growth, they are not overly restrictive in the light of the usual difficulties of estimating any stock relationship. Finally, the benefits of consuming species I and II are represented by the quadratic functions

$$B_I(Q_1(t) + \Omega_2(t)) = b_0[Q_1(t) + \Omega_2(t)] - 0.5b_1[Q_1(t) + \Omega_2(t)]^2 \tag{7}$$

and

$$B_{II}(Q_2(t) + \Omega_1(t)) = \beta_0[Q_2(t) + \Omega_1(t)] - 0.5\beta_1[Q_2(t) + \Omega_1(t)]^2, \tag{8}$$

with

$$C_1(e_1(t)) = c_1e_1(t) \text{ and } C_2(e_2(t)) = c_2e_2(t) \qquad (9),(10)$$

representing total costs of fisheries 1 and 2, respectively. The expected present value of net benefits arising from the combined fisheries is then

$$E_0 \sum_{t=0}^{\infty} \{B_I(Q_1(t) + \Omega_2(t)) + B_{II}(Q_2(t) + \Omega_1(t)) - C_1(e_1(t)) - C_2(e_2(t))\}\rho^t \tag{11}$$

where E_z represents the expectation taken at time z and ρ is the time discount factor. Equation (11) measures social economic welfare under the various regulatory regimes.

We first consider an idealized first-best situation, representing centralized control of both fisheries. The authorities thus control e_1 and e_2 in all periods in order to maximize (11), above.[4] Let $V_j^F(X_I(j),X_{II}(j))$ equal expected net social benefits, as of period j, when optimal effort levels are applied from period j into the indefinite future. Then

$$V_j^F(X_I(j),X_{II}(j)) = \text{Max } E_j \sum_{t=j}^{\infty} \{B_I(Q_1(t) + \Omega_2(t)) + B_{II}(Q_2(t) + \Omega_1(t)) - C_1(e_1(t)) - C_2(e_2(t))\}\rho_t \tag{12}$$

and, by recursion,

$$V_j^F(X_I(j),X_{II}(j)) = \max_{[e_1(j),e_2(j)]} E_j\{B_I(Q_1(j) + \Omega_2(j)) + B_{II}(Q_2(j) + \Omega_1(j)) - C_1(e_1(j)) - C_2(e_2(j)) + \rho V_{j+1}{}^F(X_I(j+1),X_{II}(j+1))\}. \tag{13}$$

[4] We assume here that effort decisions are taken after the state of nature is revealed, so that the first-best scenario represents a full-information optimum.

General first-order conditions for (13) require setting effort in each fishery to take account of the effects on the combined net benefits, as well as the costs associated with stock decline. For given values of the random variables these conditions are:

$$(B_I' - \rho\phi_1 \partial V_{j+1}{}^F/\partial X_I)\partial Q_1/\partial e_1 + (B_{II}' - \rho\phi_3 \partial V_{j+1}{}^F/\partial X_{II})\partial \Omega_1/\partial e_1 - c_1 = 0, \tag{14}$$

and

$$(B_{II}' - \rho\phi_3 \partial V_{j+1}{}^F/\partial X_{II})\partial Q_2/\partial e_2 + (B_I' - \rho\phi_1 \partial V_{j+1}{}^F/\partial X_I)\partial \Omega_2/\partial e_2 - c_2 = 0 \tag{15}$$

where primes denote the derivatives of the relevant functions. The determination of the optimal effort levels thus accounts for the cross effects of the bycatches, as well as the effects of the depletion of both stocks. The equilibrium values of catch and effort determined from (14) and (15) depend on the realized values of the random variables θ_I and θ_{II}. In principle, the value of expected net benefits is then determined by substituting $e_1(\theta_I,\theta_{II})$ and $e_2(\theta_I,\theta_{II})$ into (13) and taking expectations over the values of θ_I and θ_{II}. Utilizing a second-order Taylor series approximation in the two state variables, the optimal net benefit function may be specified as

$$\begin{aligned} V_j{}^F(X_I(j),X_{II}(j)) = {} & a_0{}^F(j) + a_1{}^F(j)X_I(j) + a_2{}^F(j)X_{II}(j) + a_3{}^F(j)X_I(j)X_{II}(j) \\ & + 0.5a_4{}^F(j)X_I(j)^2 + 0.5a_5{}^F(j)X_{II}(j)^2. \end{aligned} \tag{16}$$

Substituting from the stock growth functions (5) and (6), the problem can be converted to one of choosing e_1 and e_2 to maximize the following current-period function:[5]

$$\begin{aligned} V^F(X_I,X_{II}) = {} & E\{B_I(Q_1 + \Omega_2) + B_{II}(Q_2 + \Omega_1) - C_1(e_1) - C_2(e_2) + \rho[a_0{}^F \\ & + a_1{}^F[\phi_0 + \phi_1[X_I - Q_1 - \Omega_2]] + a_2{}^F[\phi_2 + \phi_3[X_{II} - Q_2 \\ & - \Omega_1]] + a_3{}^F[\phi_0 + \phi_1[X_I - Q_1 - \Omega_2]][\phi_2 + \phi_3[X_{II} - Q_2 \\ & - \Omega_1]] + 0.5a_4{}^F[\phi_0 + \phi_1[X_I - Q_1 - \Omega_2]]^2 + 0.5a_5{}^F[\phi_2 \\ & + \phi_3[X_{II} - Q_2 - \Omega_2]]^2]\}. \end{aligned} \tag{17}$$

The first-order conditions associated with (17) are equivalent to (14) and (15), and facilitate explicit computation in the subsequent simulations.[6] The resultant first-

[5] Because the infinite horizon problem has been converted into one involving only current period variables, period references are dropped from (17) and subsequent formulae. See Chow (1975) for a discussion of this dynamic programming technique.

[6] Given that the dynamic program involves an infinite horizon, an equilibrium must entail $a_i{}^F(j) = a_i{}^F(j+1)$, $\forall$ i,j. In the computer simulation: (1) we begin with initial guesses for $a_i{}^F(j+1)$, $\forall$ i; (2) use (14) and (15) to solve for $e_1 = e_1(\theta_I,\theta_{II}; \ldots)$ and $e_2 = e_2(\theta_I,\theta_{II}; \ldots)$; (3) substitute these expressions into (17) and take expectations over the values of θ_I and θ_{II}; (4) use a second-order Taylor series expansion in X_I and X_{II} to generate $a_i{}^F(j)$, $\forall$ i; (5) compare $a_i{}^F(j)$ with $a_i{}^F(j+1)$, $\forall$ i; (6) if the difference is within the requested accuracy a

best optimum represents the full information benchmark against which we compare the other cases.

The competitive, open-access fishery represents the opposite extreme from first-best regulation. In conformity with Weitzman (1974), Koenig (1984) and most other analyses of regulation under uncertainty, we assume the competitive equilibrium to be also a full-information one, so that the fishery participants know the values of θ_I and θ_{II} when making effort decisions. This reflects an interpretation of the uncertainty as a lack of information about the fishery on the part of government regulators rather than a technological characteristic of the search for a catch (cf. Androkovich and Stollery (1989)). Thus effort will be applied in both fisheries to the point where actual profits are zero, or

$$B_I'(Q_1 + \Omega_2)Q_1(e_1,X_I,\theta_I) + B_{II}'(Q_2 + \Omega_1)\Omega_1(e_1,X_{II},\theta_{II}) - c_1e_1 = 0 \quad (18)$$

and

$$B_{II}'(Q_2 + \Omega_1)Q_2(e_2,X_{II},\theta_{II}) + B_I'(Q_1 + \Omega_2)\Omega_2(e_2,X_I,\theta_I) - c_2e_2 = 0. \quad (19)$$

The derivatives of the total benefit functions denote the prices in each market, which are assumed to apply equally to primary catch or bycatch. The resulting effort and catch levels are functions of θ_I and θ_{II}. When these are substituted into the competitive analogue of (17) and expectations are taken, the expected present value of the combined fisheries net social benefits is obtained. A competitive fishery of course overutilizes the resource because of the destructive competition associated with the usual stock externality. In our case, the bycatch creates an externality with respect to both stocks.

Practical regulation of the fishery involves indirect control through various incentive mechanisms, and because of the assumed lack of information about fishery productivity, is necessarily second best.[7] We model taxes and global quotas as the usual regulatory methods, and represent the lack of information on the part of the authorities by requiring these instruments to be set prior to the realization of the random variables.

Because of the practical difficulties of distinguishing the origin of a given catch, we assume the regulators are only able to set specific taxes on the landings of each species irrespective of origin; taxes which we denote by τ_I and τ_{II}. Given these prespecified taxes, the zero profit conditions now imply

$$[B_I' - \tau_I]Q_1(e_1,X_I,\theta_I) + [B_{II}' - \tau_{II}]\Omega_1(e_1,X_{II},\theta_{II}) - c_1e_1 = 0 \quad (20)$$

and

solution has been found; (7) if the difference is 'too large' then new values for $a_i^F(j + 1)$, $\forall i$ are generated and the process is repeated until the system converges.

[7] There are several other possible sources of uncertainty; concerning the effort costs, or the levels or growth rates of the stocks, for example. We do not model these because they have been considered elsewhere, and because we wish to focus on the bycatch issue. For a survey of uncertainty in fishery models see Andersen and Sutinen (1986), or Anderson (1986).

$$[B_{II}' - \tau_{II}]Q_2(e_2,X_{II},\theta_{II}) + [B_I' - \tau_I]\Omega_2(e_2,X_I,\theta_I) - c_2e_2 = 0. \tag{21}$$

Thus effort in each state now depends on the tax rates, which the authorities optimally set to maximize the tax equivalent of (12), subject to (20) and (21) and the stock recursion functions (5) and (6). Comparison of (20) and (21) with the first-best optimal conditions (14) and (15) indicate that, were it possible to set taxes with full information on θ_I and θ_{II}, taxes of $\tau_I = \rho\phi_1\partial V_{j+1}{}^F/\partial X_I$ and $\tau_{II} = \rho\phi_3\partial V_{j+1}{}^F/\partial X_{II}$ would mimic the first-best optimum. That this is not possible is the result of the lack of information on the part of the authorities.

For purposes of comparison we also consider an un-coordinated tax system in which each fishery is managed in isolation, with taxes on the primary catch but not on the bycatch. Such a system is necessarily suboptimal, but we employ simulation in a later section to assess the magnitude of the loss of net benefits relative to optimal taxation.

We complete the theoretical analysis by considering a dual quota scheme. Let Q_I and Q_{II} represent the quotas imposed by the regulatory authority on the primary catch of species I by fishery one, and species II by fishery two, respectively. These primary catch quotas are sufficient to control both effort and bycatch in an expected value sense, as the inverted primary and bycatch production functions give

$$e_1 = Q_i/k_1X_I\theta_I; \qquad \Omega_1 = (k_2/k_1)(\theta_{II}/\theta_I)(X_{II}/X_I)Q_I \tag{22}$$

$$e_2 = Q_{II}/w_2X_{II}\theta_{II}; \qquad \Omega_2 = (w_1/w_2)(\theta_I/\theta_{II})(X_I/X_{II})Q_{II}. \tag{23}$$

The quota managers set Q_I and Q_{II} (again prior to the realization of the random variables) in order to maximize the quota equivalent of equation (12).

Calibration and Estimation

If the model described above is to be applied to actual fisheries, the information requirements are substantial. Parameters describing the demand, cost and production relationships are required for two fisheries, while the parameters which characterize the biological relationships for the two fish stocks must also be adequately specified. Fortunately, the information we require has been collected for cod and haddock in the Northwest Atlantic Fisheries Organization area 4X, representing Brown's Bank, Nova Scotia. These two species were selected because they are both important groundfish and hence the cod fishery's bycatch of haddock, for instance, is likely to be significant. Area 4X was chosen because it has one of the highest bycatch problems of any Canadian east-coast management area, and with about 50% of the Atlantic Canada haddock catch it is one of the most important suppliers of that species.

Area 4X has had a long regulatory history for both cod and haddock stocks. Traditionally, the inshore, small-boat fleet took the main haddock catch, with about 80% of the 1948–61 average of 15,000 tonnes.[8] However, the influx of a

[8] Background material on cod and haddock management in this area was taken largely from Rivard *et al.* (1988) and from CAFSAC Advisory Committee Document 89/12 (1989) from the Canadian Department of Fisheries and Oceans.

large offshore trawler fleet in the 1960's caused a rapid increase in catch rates, peaking in 1965 at over 40,000 tonnes and, in 1970, prompting the very first total allowable catch quota (TAC) imposed by the international fishery regulatory body.[9] Current haddock catches are again about 15,000 tonnes. Cod landings are of similar magnitude at an average of 22,000 tonnes, ranging from 12,000 to 36,000 tonnes since 1948. The landings of the two species are highly correlated, the importance of bycatch being illustrated by the fact that the haddock quotas of the early 1970's reduced cod landings from over 35,000 tonnes in the late 1960's to 22,000 tonnes by 1972. Area 4X cod landings, while of about equal size to the haddock catch, are only about 10% of the Atlantic Canada total and are of much less importance to the overall market. Regulation of the area 4X cod fishery also began in the early 1970's.

Parameters for our simulated bycatch management were obtained by estimating demand and stock growth relationships for both fisheries, and by calibrating the model to a 1969 benchmark.[10] The linear (inverse) demand equation estimated for haddock in area 4X for the period 1962–84 (with t-ratios in parenthesis) is

$$\begin{aligned} \text{Haddock: } P_h &= \underset{(1.97)}{192.16} + \underset{(4.32)}{2.06Y^C} - \underset{(3.15)}{0.0056Q_h^{4x}}, \\ &\qquad R^2 = 0.81,\ \text{D.W.} = 1.95. \\ &\qquad \text{Method: M.A. (2)} \end{aligned}$$

Here P_h stands for the haddock price in 1961 dollars per tonne, Y^C represents Canadian real income, and Q_h^{4x} denotes the area 4X haddock catch in tonnes.[11] For 1969 demand, Y^C is set at that year's level, yielding

$$\text{Haddock: } P_h = 633.78 - 0.0056Q_h^{4x}.$$

Specifying haddock as species II of the theoretical model, it follows that our estimates of β_0 and β_1 are 633.78 and 0.0056, respectively. These parameters imply an own-price elasticity at the sample mean of approximately -2, which is as expected given that area 4X is a subregion of a larger fishery and that haddock is a substitute for other groundfish.

An area 4X cod demand function could not be estimated directly because its small share of total supply (about 8.9% during the period 1962–84) made price

[9] The fishery was first managed by the International Commission for Northwest Atlantic Fisheries (ICNAF), now the Northwest Atlantic Fisheries Organization (NAFO). After the 200 mile exclusive Canadian management zone was established in 1977, it has been managed by the Canadian Department of Fisheries and Oceans.

[10] This benchmark was chosen because the year just preceded the introduction of quota management in the two fisheries, and may be taken to represent open-access equilibrium.

[11] Demand was estimated in inverse form to reduce simultaneous equation bias. Q_h^{4x} could be taken as exogenous for most of the sample period because it was regulated by quota. (A Chow test confirms that the pre- and post-1970 coefficients are not significantly different.) Data on prices were obtained from the Canadian Department of Fisheries and Oceans *Annual Statistical Review of Canadian Fisheries,* and on Area 4X catch from O'Boyle *et al.* (1989) and Campana *et al.* (1989) and the NAFO *Statistical Bulletins*. It should be noted that the initial specification of the demand equation included a cross-price effect, but multicollinearity between the substitute price and the real income variable made both coefficient estimates unreliable, so only the income variable was retained. The same problem arose when estimating the demand for cod.

unresponsive to this area's catch rate. Instead, we estimated a demand equation for Canada's total east coast cod catch, which was then used to characterize the demand for cod in area 4X. With P_c the price and Q_c^C the total Canadian catch of cod, the estimated equation is

$$\text{Cod: } P_c = \underset{(9.12)}{193.73} + \underset{(10.77)}{0.87Y^C} - \underset{(7.25)}{0.00035Q_c^C},$$

$R^2 = 0.96$, D.W. = 1.74.
Method: M.A. (2)

In 1969 the cod catch in 4X (Q_c^{4X}) represented eleven per cent of the Atlantic Canada total. Utilizing this information, and again setting Y^C at its 1969 level, the benchmark demand for the cod in area 4X was obtained as

$$\text{Cod: } P_c = 378.89 - 0.0031Q_c^{4x};$$

hence $b_0 = 378.89$ and $b_1 = 0.0031$, with an elasticity of -2.3, consistent with other studies of cod demand.[12]

Regression analysis was also used to estimate the parameters of the stock growth equations. Because of closures and other restrictions in the Nova Scotia fisheries, the commercial catch per unit effort (CPUE) is not considered by fishery experts to be a reliable indicator of stock abundance. We therefore used independent estimates for the haddock and cod stocks developed on the basis of research vessel surveys and cohort analysis by Canadian Department of Fisheries and Oceans biologists at the Bedford Institute of Oceanography in Nova Scotia, published in O'Boyle *et al.* (1989) and Campana *et al.* (1989) for haddock and cod respectively. The estimated growth equations using these stock data were

$$\text{Cod: } X_c^{4X}(t) = \underset{(5.76)}{55325.0} + \underset{(2.58)}{0.41}[X_c^{4X}(t-1) - Q_c^{4X}(t-1)],$$

$R^2 = 0.76$, D.W. = 2.07,
Method: Auto(1)
Sample: 1948–1988

and

$$\text{Haddock: } X_h^{4X}(t) = \underset{(5.44)}{66932.0} + \underset{(2.82)}{0.30}[X_h^{4X}(t-1) - Q_h^{4X}(t-1)],$$

$R^2 = 0.90$, D.W. = 1.20.
Method: Auto(2)
Sample: 1962–1988

These give parameter estimates $\phi_0 = 55325.0$, $\phi_1 = 0.41$, $\phi_2 = 66932.0$ and $\phi_3 = 0.30$.[13]

[12] Tsoa, Schrank and Roy (1981) estimated the cod demand at wholesale level as -0.76 for fillets and -2.89 for blocks. Overall landings go to both destinations.

[13] The stock growth equations—(5) and (6)—are best regarded as approximations which are accurate in the neighbourhood of the levels of escapement. An immediate concern is whether the approximations that are appropriate for the first-best scenario are also appro-

The determination of the production function parameters and per-unit effort costs in each fishery required estimates of aggregate effort. We were fortunate, however, in that O'Boyle *et al.* (1989) and Campana *et al.* (1989) reported standardized effort measures—representing weighted averages of effort for various gear types—for the two fisheries. In 1969, 34,299 units of effort were applied in the haddock fishery. With a haddock stock of 70,000 tonnes and a primary catch of 22,435 tonnes, we calibrated w_2 to a value of 9.34×10^{-6}. As regards the haddock fishery's bycatch of cod, a cod stock of 81,124 tonnes and a cod bycatch of 7556 tonnes implies w_1 equal to 2.72×10^{-6}. The characterization of the benchmark primary cod catch and haddock bycatch was more difficult as effort estimates for the cod fishery were only available for the period 1976–88, and we were thus forced to follow an indirect approach in obtaining values for k_1 and k_2. Recall that the haddock bycatch is given by $\Omega_1 = k_2 e_1 X_{II}$; where e_1 represents standardized effort in the fishery directed at cod, and X_{II} represents the haddock stock. It follows that we were able to directly relate the haddock bycatch per unit of cod fishery effort (Ω_1/e_1) to the haddock stock (X_{II}). This equation was then estimated for the period 1976–88; yielding k_2 equal to 9.30×10^{-7}. Once this exercise was completed, we calibrated the cod fishery's 1969 effort level to a benchmark of 122,309 units by substituting the estimated value for k_2, along with data on the haddock bycatch and stock for 1969, into the equation $e_1 = \Omega_1/k_2X_{II}$. And finally, the information already reported allowed us to characterize the primary cod catch by setting k_1 equal to 2.54×10^{-6}.[14]

The cost of effort parameters were also specified indirectly, from the assumption of competitive behavior in the benchmark year. Given the haddock fishery's effort of 34,299 units and the cod fishery's benchmark effort of 122,209 units, we set c_1 and c_2 equal to \$86.22 and \$359.51, respectively, so that the model was calibrated to a situation of zero profits in the two fisheries.[15]

To this point we have specified the parameters for the demand, cost, growth and production relationships. We are left with having to account for the inherent uncertainty of the situation, *i.e.*, the random variables θ_I and θ_{II}. Given the value for k_1, we assume that fluctuations over time in the primary cod catch per unit of standardized effort are due to θ_I, enabling us to obtain 2.19×10^{-2} as the estimate for the Var(θ_I). An analogous exercise yields 3.87×10^{-2} as the estimate for Var(θ_{II}).[16]

priate for other scenarios. That is, whether the values specified for ϕ_0, ϕ_1, ϕ_2 and ϕ_3 should be identical for the various cases. Unfortunately, the data which was available precluded us from addressing this issue, and we were forced to utilize the same set of parameter values in completing the simulation exercise.

[14] The relative magnitudes of primary catch and bycatch were calculated from the Northwest Atlantic Fisheries Organization's *Statistical Bulletins*. To distinguish between primary and bycatches we adopted the following rule of thumb: if for a particular gear category the cod catch, for instance, is the largest in terms of weight then that particular catch is counted as a primary catch. So as to account for the entire cod catch we assumed the remainder to represent the bycatch for the haddock fishery.

[15] If the difference in per-unit effort costs in the two fisheries appears unusual, recall that the standardized effort measure we are using may mask considerable differences in effort cost, depending on the proportions of the different gear types employed.

[16] With respect to the simulation exercise, we assume that both θ_I and θ_{II} are distributed according to uniform density functions with limits obtained from the estimates for Var(θ_I) and Var(θ_{II}).

Simulation Results

Having specified the models' parameters, we are now able to compare the various regulatory alternatives, including the expected net benefits of coordinated optimal tax and quota regulation in both fisheries as opposed to uncoordinated regulation of each fishery separately. For each of the models specified in section 2 we solve the respective dynamic programs, with the results reported in Table I.[17] The competitive, open access fishery represents one benchmark for comparison. In the simulated equilibrium the cod and haddock fisheries apply 116,456 and 27,474 units of (standardized) effort, respectively, resulting in expected total catches (primary plus bycatch) of 31,428 and 28,166 tonnes. The expected net social benefits resulting from the operation of the two fisheries is $125.41 million.

The opposite extreme from open-access is represented by the idealized first-best equilibrium. Here full information is also assumed but the fishery is fully centralized, with the regulators able to take account of all externalities. The result is a decline in cod and haddock effort of 37.6 and 53.4 per cent, respectively, relative to the competitive case, and an increase in expected net social benefits of 12 per cent. The reason, of course, is the elimination of the "destructive competition" associated with the stock externality.

Practical fishery regulation represents decentralized control in a situation of limited information about the fishery. Optimal, coordinated taxation takes into account the simultaneity created by the bycatches. We find the optimal tax on cod to be $36.65 per tonne, and on haddock to be $63.56 per tonne; both representing approximately 12 per cent of the respective industry price. The induced reductions in effort and catch result in combined fishery expected net social benefits of $139.6 million, eliminating 94.5 per cent of the $15 million loss in social welfare that is a consequence of competitive behaviour.

[17] It is important to recall at this stage that effort decisions are assumed to be taken after the state of nature is revealed. Thus we can only report expected effort levels (and expected catch rates) in Table I.

Table 1
The Net Social Benefits of Various Regulatory Regimes in the Area of 4X Fishery

	Full Information		Limited Information		
	Competitive	First Best	Coordinated Taxes	Uncoordinated Taxes	Quotas
Cod tax	—	—	36.65	57.20	—
Haddock tax	—	—	63.56	73.49	—
Cod Quota	—	—	—	—	16.22
Haddock Quota	—	—	—	—	10.64
Cod effort	116.46	72.66	72.97	71.09	80.62
Haddock effort	27.47	12.80	13.70	15.23	16.94
Expected Cod Catch	31.43	19.75	19.71	19.47	19.96
Haddock Catch	28.17	16.59	16.80	17.47	15.89
ENSB	125.41	140.42	139.60	138.21	120.61

Note: The expected outputs and quotas are measured in thousands of metric tonnes, the tax rates are dollars per metric tonne and effort is in thousands of standardized units. Expected net social benefits (ENSB) for the two fisheries combined are given in millions of 1969 dollars.

It is possible that fisheries would be regulated in isolation, without recognition of their interdependence. As is shown in the fourth column of Table I, the case of uncoördinated taxation requires higher taxes relative to the coordinated tax case to induce the fishery participants to recognize the social costs of stock depletion. The reason is that only with coordinated taxation do the authorities recognize that a tax on cod will benefit the haddock stock and *vice versa*. Although there is a relatively small loss of social welfare as the result of the lack of coordination (eliminating 85 rather than 95 per cent of the competitive industry loss) the main effect is a transfer of rents from producers to the government.

Instead of operating indirectly through the price mechanism, quotas control the two primary catches directly. The optimal primary catch quotas on cod and haddock are calculated at 16,222 and 10,639 tonnes respectively, as compared with expected total catches of 19,955 and 15,887 tonnes. The total (expected) catch for each fishery exceeds its quota because the dual-quota scheme controls the bycatches only indirectly, through both random variables (equations (22) and (23)). That the quota scheme is dominated by the tax scheme in terms of expected net social benefits is to be expected (see Koenig (1984)), but our finding that the quota is inferior to a competitive environment is, at least initially, surprising. The paradox is resolved when one recalls that the economic agents in the competitive case are assumed to have full information when making decisions, while both tax and quota decisions must be made under uncertainty. It is this cost of uncertainty that makes the inferiority of quotas possible. The low ranking of quotas relative to taxes is caused by the greater flexibility of the latter under uncertainty. In a setting where the effort levels are determined *ex post*—that is, after the realization of the random variables—the imposition of rigid quotas represents a fundamental intrusion into the process by which effort is determined. Instead of observing how changes in θ_I and θ_{II} will affect the profitability of the situation and responding with appropriate effort decisions, the two fisheries will choose effort levels which ensure that the quotas are satisfied. Fluctuations in θ_I and θ_{II} will induce larger adjustments in e_1 and e_2 when rigid quotas are in place, and these amplified adjustments in effort will, in turn, entail welfare losses when comparing quotas with both the competitive and tax environments. Continuing with this line of argument, we speculate that if the situation somehow became 'less uncertain' the fundamental problem with quotas would be lessened. In order to test this hypothesis we reduced $\mathrm{Var}(\theta_I)$ and $\mathrm{Var}(\theta_{II})$ to 50% of the values reported previously, and found that taxes continued to dominate quotas, while the quota scheme dominated competitive behaviour.

Conclusions

The presence of incidental catch introduces important interdependencies which significantly complicate fishery regulation. We compared the optimal, coordinated taxation of the Nova Scotian cod and haddock fisheries with the independent taxation of each fishery separately (ignoring the interdependencies created by the presence of bycatch). We find that while the independent taxation can almost equal optimal taxation in terms of net social benefits, the fact that bycatch is ignored means that significantly higher taxes on primary catch are required to preserve the stock. The result is a large transfer of rents from producers to the government, unnecessarily increasing the unpopularity of taxes as a regulation method. Catch quotas, in contrast, appear a much inferior method in the presence of uncertainty and a significant bycatch. The reason is the quota's lack of flexibility in the presence of uncertain fishery productivity, and its much more indirect bycatch control.

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