Australian Agricultural and Resource Economics Society

Contributed Paper, AARES 48th Annual Conference, 11-13 February 2004, Melbourne

Taxes vs Quotas for Regulating Fisheries under Uncertainty

John Kennedy

Department of Economics and Finance, La Trobe University, Melbourne, Victoria 3086
j.kennedy@latrobe.edu.au

and

Rögnvaldur Hannesson

The Norwegian School of Economics and Business Administration,
Helleveien 30, N-5045 Bergen, Norway
rognvaldur.hannesson@nhh.no

Abstract

The overexploitation of fish stocks under open access conditions can be controlled by imposing a unit tax on fish landed or a quota on the total catch each season. Under certainty, both instruments can be used to achieve total catches that are economically efficient. Weitzman has recently shown that if the regulator has to set the tax or quota before being certain of the beginning-of-season stock level, whereas fishers subsequently react to the tax or quota knowing with certainty the beginning-of-season stock, taxes but not quotas can always be used to achieve the objective.

In the paper the result is obtained by a simpler method. It is also used to show how the tax for the current season which is optimal for an extended planning horizon relies only on knowing the economic and growth parameters for the current and immediately following seasons. These insights and the numerical results from a stochastic dynamic programming model are used to investigate which instrument is more efficient for other sources of uncertainty facing the regulator besides stock uncertainty, such as uncertainty about fish price and the availability of fish.

Key words: Fisheries regulation, parameter uncertainty, dynamic programming

This paper is posted at the following URL:
http://www.business.latrobe.edu.au/staffhp/jkennedy/

Taxes vs Quotas for Regulating Fisheries under Uncertainty

John Kennedy and Rögnvaldur Hannesson

1. INTRODUCTION

An unregulated open-access fish stock is analysed as being exploited too heavily in the short run. The resulting present value of the future stream of economic rents is lower than the efficient level. The inefficiency arises from fishers being unable to claim proprietary rights over any current catch foregone in the interest of obtaining a higher future return.

Various regulatory systems can be used to increase returns from an open-access fishery, operating on either fishers' effort inputs or on their catch output. All systems of course have regulatory costs which may be difficult to measure, so the best system is generally difficult to identify. Taxes and quotas on inputs are costly if the number of substitutable inputs is large. Taxes and quotas on catch may be simpler systems, although difficulties arise if more than one species is caught.

From a deterministic bioeconomic model of a fishery the optimal tax or fee placed on landed fish, or the quota on catch, can be calculated which would maximise the present value of economic rents before charging for regulatory costs. The choice between the two instruments would depend on differential regulatory costs. The choice is more complex if model parameters are uncertain. For example, it might be thought if the level of stock at the start of a fishing season is uncertain, quotas would be a more reliable and effective instrument. However, Weitzman (2002) has shown that for a particular type of stock uncertainty fees rather than quotas dominate, ignoring for simplicity differential regulatory costs. The result holds for a case of asymmetric information. Fishers know the start-of-season stock level, made up of an earlier known stock level plus a recent random component. However, the regulator has to set either the fee or the quota without knowing the random stock component.

Weitzman refers to this type of stock uncertainty as ecological uncertainty. He explicitly leaves it as an open question still to be resolved which instrument may dominate for other types of uncertainty; for example, uncertainty about economic parameters such as prices and costs, and about technical catchability coefficients. Hannesson and Kennedy (2003) have investigated these issues using a simulation model across wide ranges of parameters for distributions of the price of fish, cost of fishing effort, availability of fish to capture, and the stock exponent in the traditional catch function. The main conclusion is that there can be no presumption that fees dominate quotas as the regulatory instrument when other sources of uncertainty besides stock levels apply.

The advantage of simulation for investigating these issues is that results can be readily obtained for a large range of parameter values. A disadvantage is that only reasonable approximations can be made to modelling the assumed long-run optimising behaviour of regulators. Of course, it is questionable how realistic the assumption of optimising behaviour is. In this paper we adopt an optimising approach.

Two extensions to Weitzman's results are considered. One is to show under what circumstances the superiority of fees over quotas is not dependent on formulating the regulator's problem with an infinite planning horizon and a season-invariant rent function and state transition equation. Secondly it is argued that fees and quotas could achieve the same maximum present value of rents for the case of the additive random stock term, if this is known to the regulator before setting the fee or quota for the season

As the limitations of an analytical approach become evident, we turn to obtaining some numerical results for different sources of uncertainty using dynamic programming methods.

2. STOCHASTIC STOCK TRANSITION AND DETERMINISTIC RENT FUNCTION

Suppose that stock after growth but before harvest includes an additive random component. The price of fish is independent of the catch. We will start by considering two alternative problems a sole fisher may face in determining harvest H_t in each season *t* so as to maximise the expected present value of rents over *n* fishing seasons. The rent and growth functions used are similar to those used by Hannesson and Kennedy (2003), and are specified with parameter values in the numerical modelling in section 3.

2.1 Sole fisher's harvest for maximum expected present value of rents

In the first problem the fisher knows the random stock term before harvesting, in the second he does not.

2.1.1 Start-of-season stock known

Rent is the following function of start-of-season stock x_t and harvest:

$$\pi_t\{x_t, H_t\} = p_t H_t - c_t\{x_t, x_t - H_t\} \quad \forall t \tag{1}$$

where p_t is the price of fish harvested and c_t is the cost of the harvest, a function of the start-of-season stock, and the end-of-season stock $(x_t - H_t)$. Second-order partial derivates are $\pi_{t11} > 0$ and $\pi_{t22} < 0$.

The stock in season $t+1$, after growth and random events, and immediately prior to the start of harvesting, is:

$$x_{t+1} = x_t - H_t + g_t\{x_t - H_t\} + \varepsilon_{x,t} \quad \forall t \tag{2}$$

where $g_t\{x_t - H_t\}$ is growth a function of end-of-season stock with $g_{HH} > 0$, and $\varepsilon_{x,t}$ is a random variable.

The sole fisher's problem is:

$$\max_{H_1,\ldots,H_n} \underset{\varepsilon_{x,1},\ldots,\varepsilon_{x,n}}{E}\left[\sum_{t=1}^{n} \pi_t\{x_t, H_t\}/(1+r)^t\right] = V_1\{x_1\} \qquad (3)$$

subject to stock updating equation (2) and x_1 given. Seasons occur annually, and *r* is the rate of discount *per annum*.

To facilitate solution of (3), the multi-decision problem can be equivalently expressed as *n* single-stage decision problems, using the recursive functional equation:

$$V_t\{x_t\} = \max_{0 \le H_t \le x_t}\left(\pi_t\{x_t, H_t\} + \underset{\varepsilon_{x,t}}{E}\left[V_{t+1}\{x_t - H_t + g_t\{x_t - H_t\} + \varepsilon_{x,t}\}/(1+r)\right]\right) \quad t = 1,\ldots,n \qquad (4)$$

The first order condition for an interior solution to (4) for the setting of H_t^* $(t = 1,\ldots,n)$ is[1]:

$$\frac{\partial \pi_t}{\partial H_t} + \underset{\varepsilon_{x,t}}{E}\left[\left.\frac{dV_{t+1}}{dx_{t+1}}\right|_{x_t - H_t + g_t\{x_t - H_t\} + \varepsilon_{x,t}}\right]\left(-1 + \frac{\partial g_t}{\partial H_t}\right)/(1+r) = 0 \qquad (5)$$

The term $\dfrac{dV_{t+1}}{dx_{t+1}}$ is the shadow price of one unit of stock at the beginning of season $t+1$. Its value is obtained by differentiating (4) with respect to x_t:

$$\frac{dV_t}{dx_t} = \frac{\partial \pi_t}{\partial x_t} + \underset{\varepsilon_{x,t}}{E}\left[\left.\frac{dV_{t+1}}{dx_{t+1}}\right|_{x_t - H_t + g_t\{x_t - H_t\} + \varepsilon_{x,t}}\right]\left(1 + \frac{\partial g_t}{\partial x_t}\right)/(1+r) \quad \forall t \qquad (6)$$

From the partial derivatives of (2) with respect to H_t and x_t:

$$\left(-1 + \frac{\partial g_t}{\partial H_t}\right) = -\left(1 + \frac{\partial g_t}{\partial x_t}\right) \quad \forall t \qquad (7)$$

---

[1] By the Kuhn-Tucker conditions, the alternative conditions for the lower and upper bound solutions for H_t (0 and x_t respectively) are for the left-hand side to be ≤ 0 or ≥ 0 respectively, assuming the expected present value of rents is a concave function of H_t. The rent function is concave in H_t for the signs of the partial derivatives of provided π and *g*, and provided $dV/dx > 0$.

Substituting the right-hand side of (7) for the left-hand side of (7) in (5), (5) for an interior solution becomes:

$$\underset{\varepsilon_{x,t}}{E}\left[\left.\frac{dV_{t+1}}{dx_{t+1}}\right|_{x_t-H_t+g_t\{x_t-H_t\}+\varepsilon_{x,t}}\right]\left(1+\frac{\partial g_t}{\partial x_t}\right)/(1+r)=\frac{\partial \pi_t}{\partial H_t}\quad \forall t \qquad (8)$$

After substituting the right-hand side of (8) for the left-hand side of (8) in (6), for an interior solution (6) becomes:

$$\frac{dV_t}{dx_t}=\frac{\partial \pi_t}{\partial x_t}+\frac{\partial \pi_t}{\partial H_t}\quad \forall t \qquad (9)$$

The left-hand side is the shadow price of a unit of stock at the beginning of season *t*. The right-hand side is the sum of the two partial derivatives of (1), which simplifies to:

$$\frac{dV_t}{dx_t}=p_t-\frac{\partial c_t}{\partial x_t}\quad \forall t \qquad (10)$$

As would be predicted, the shadow price of a unit of stock at the beginning of season *t* equals the landed value of the unit plus the reduction in harvesting cost from augmenting stock by the unit.

Optimality condition (5) for an interior solution can now be written more transparently and operationally as:

$$\frac{\partial \pi_t}{\partial H_t}+\left(p_{t+1}-\underset{\varepsilon_{x,t+1}}{E}\left[\left.\frac{\partial c_{t+1}}{\partial x_{t+1}}\right|_{x_t-H_t+g_t\{x_t-H_t\}+\varepsilon_{x,t}}\right]\right)\left(-1+\frac{\partial g_t}{\partial H_t}\right)/(1+r)=0\quad \forall t \qquad (11)$$

We now consider the second, more complex, problem the sole fisher may face. This is the case where the sole fisher sets the harvest knowing the previous season's stock after growth, but before the stochastic stock event is known.

2.1.2 Start-of-season stock unknown

In the second problem the fisher does not. know the random stock term before harvesting. *Ex ante* rent resulting from the sole fisher's setting of H_t now depends on the stochastic stock event as follows:

$$\pi_t\{x_t+\varepsilon_{x,t},H_t\}=p_tH_t-c_t\{x_t+\varepsilon_{x,t},x_t+\varepsilon_{x,t}-H_t\}\quad \forall t \qquad (12)$$

The stock known to the sole fisher at the start of season $t+1$, after growth but before random events and harvesting, is:

$$x_{t+1}=x_t+\varepsilon_{x,t}-H_t+g_t\{x_t+\varepsilon_{x,t}-H_t\}\quad \forall t \qquad (13)$$

The sole fisher's problem is:

$$\max_{H_1,H_2,\ldots}\ \underset{\varepsilon_{x,1},\varepsilon_{x,2},\ldots}{E}\left[\sum_{t=1}^{n}\pi_t\{x_t+\varepsilon_{x,t},H_t\}/(1+r)^t\right]=V_1\{x_1\} \tag{14}$$

subject to stock updating equation (2) and x_1 given.

The recursive functional equation is:

$$V_t\{x_t\}=\max_{H_t}\ \underset{\varepsilon_{x,t}}{E}\left[\pi_t\{x+\varepsilon_{x,t},H_t\}+V_{t+1}\{x_t+\varepsilon_{x,t}-H_t+g_t\{x_t+\varepsilon_{x,t}-H_t\}\}/(1+r)\right]\quad t=1,\ldots,n \tag{15}$$

The first order condition for an interior solution to (15) for the setting of H_t^* $(t=1,\ldots,n)$ is:

$$\underset{\varepsilon_{x,t}}{E}\left[\frac{\partial\pi_t}{\partial H_t}+\left(\left.\frac{dV_{t+1}}{dx_{t+1}}\right|_{x_t+\varepsilon_{x,t}-H_t+g_t\{x_t+\varepsilon_{x,t}-H_t\}}\right)\left(-1+\frac{\partial g_t}{\partial H_t}\right)/(1+r)\right]=0\quad\forall t \tag{16}$$

The shadow price of one unit of stock at the beginning of season $t+1$ equals the derivative of (15):

$$\frac{dV_t}{dx_t}=\underset{\varepsilon_{x,t}}{E}\left[\left.\frac{\partial\pi_t}{\partial x_t}\right|_{x_t+\varepsilon_{x,t}}+\left.\frac{dV_{t+1}}{dx_{t+1}}\right|_{x_t+\varepsilon_{x,t}-H_t+g_t\{x_t+\varepsilon_{x,t}-H_t\}}\left(1+\left.\frac{\partial g_t}{\partial x_t}\right|_{x_t+\varepsilon_{x,t}}\right)/(1+r)\right]\quad\forall t \tag{17}$$

After substitution as before, (17) becomes:

$$\begin{aligned}\frac{dV_t}{dx_t}&=\underset{\varepsilon_{x,t}}{E}\left[\frac{\partial\pi_t}{\partial x_t}+\frac{\partial\pi_t}{\partial H_t}\right]\\&=p_t-\underset{\varepsilon_{x,t}}{E}\left[\frac{\partial c_t}{\partial x_t}\right]\quad\forall t\end{aligned} \tag{18}$$

Analagous to (11), the result for start-of-season stock known, the first order condition for an interior solution to (15) can now be written more operationally as:

$$\underset{\varepsilon_{x,t}}{E}\left[\frac{\partial\pi_t}{\partial H_t}+\left(p_{t+1}-\underset{\varepsilon_{x,t+1}}{E}\left[\frac{\partial c_{t+1}}{\partial x_{t+1}}\right]\right)\left(-1+\frac{\partial g_t}{\partial H_t}\right)/(1+r)\right]=0\quad\forall t \tag{19}$$

2.2 Regulator control settings for an open-access fishery

If harvesting is not the exclusive right of a sole fisher but is open to all, it is unlikely to result in the maximum expected present value of rents obtainable under a sole fisher. At some regulatory cost, a regulator may be appointed to use a control instrument to increase the expected present value of rents from open-access levels. Suppose the objective is to maximise the expected present value of rents. The expected present value of consumer surplus is not considered, either because only producer rents count, or because the price of fish is independent of catch and consumer surplus is therefore zero.

Following Weitzman (2002), let us suppose that catch is regulated by setting for each harvesting season either catch quotas or fees on landed fish. The best setting of the quota or fee depends on the harvesting behaviour of fishers each season under open access. Kennedy and Hannesson (2003) have investigated circumstances under which the outcome may be maximum or zero within-season rents. Here, again following Weitzman, we will assume maximum within-season rents under open access. Weitzman has points out that for a deterministic fishery, maximum present value of rents could be obtained using either instrument, but proves that for a stochastic fishery with stock at the start of the harvest season dependent on a random additive term, fees would always achieve rents equal to or higher than rents under quotas.

2.2.1 The equivalence of fees and quotas under uncertainty for the same information structure

Let Q_t be the quota setting in season *t*. If the information available to the regulator is identical to that available to the sole fisher, then the regulator will set Q_t at the same level as the sole fisher sets H_t. The open-access fishery will harvest Q_t and achieve the same expected present value of rents.

This applies to the cases where the stock transition is deterministic, and where stock depends on a random additive term. In the stochastic stock case, quota setting results in the same time profile of rents for the regulator as for the sole fisher, if both know or do not know the random term immediately before the start of fishing.

2.2.2 Optimality under limited look ahead

If for any season *t* the solution is an interior solution, satisfying (11), optimal quota Q_t depends on no price, cost, growth or stochastic-stock parameters for seasons beyond $t+1$. This is so whether the planning horizon at the start of season *t* extends to just two or to infinite seasons. This means that if the solution is an interior solution, the regulator's problem is relatively straightforward, and that analysis of the effect of the stochastic stock term is simpler.

If the open-access fishers know the stochastic stock term before the start of fishing but the regulator does not, the case considered by Weitzman, in general the regulator will not be able to set quotas which achieve the sole fisher's expected present value of rents. Further, there is no guarantee that the harvest taken by the open-access fishers will equal the quota set by the regulator. It will not be the same if harvest taken by the open-access fishers knowing the stochastic stock term is less than the quota set by the regulator not knowing the stochastic stock term.

Although the analytical derivation of the marginality conditions for optimal settings of harvests, fees and quotas under uncertainty have the important advantage of some generality, we have not been able to draw any conclusions from the analysis on the relative performance of fees versus quotas. To draw some insights on this, in the next section recursive equations are developed for problems with fees and quotas as the policy instruments. Numerical solutions to these problems are obtained for particular parameter values and three sources of uncertainty.

3. NUMERICAL RESULTS FOR STOCK, PRICE AND CATCH UNCERTAINTY

In this section the aim is to determine the comparative performance of fees and quotas in capping harvests each season so as to maximise the present value of expected rents. Which instrument results in the larger flow of rents over the long run? Does the comparative performance depend on which of the variables stock, price and availability to fishing are stochastic? To answer these questions for particular functions and parameter values, it is assumed that all stage functions are the same for all stages, and that the number of policy stages is infinite.

3.1 Function specification

The growth function is

$$g\{x\} = ax(1 - x/K) \tag{20}$$

where a is the intrinsic growth rate and K is the carrying capacity of the environment.

The harvest function is

$$h = Eqx \tag{21}$$

where h is the number of fish harvested from fishing effort E, and q is a measure of availability of fish to capture.

If c is the cost per unit of fishing effort, then the cost of catching one fish is $c/(qx)$. Rent for the season from harvesting stock down from start-of-season stock x_1 to end-of-season stock x_2 is

$$\begin{aligned} \pi &= \int_{x_2}^{x_1} [p - c/(qx)]dx \\ &= p(x_1 - x_2) - (c/q)[\ln(x_1) - \ln(x_2)] \end{aligned} \tag{22}$$

The season's rent is maximised by fishing down to the x_2 for which marginal rent is zero, or

$$p - c/(qx_2) = 0 \tag{23}$$

resulting in $x_2 = c/(pq)$. It is assumed that this is the end-of-season stock targeted by open-access fishers.

The values of parameters in functions (20) to (22) are given in Table 1.

Table 1: Parameter values

Parameter		Value
Mean price of fish	$\bar{p}$	1.00
Mean availability of fish	$\bar{q}$	1.00
Cost per unit of fishing effort	c	0.10
Intrinsic growth rate	a	0.50
Carrying capacity	K	1.00
Rate of discount	r	0.00

Solutions are obtained numerically. The opening-stock after-growth state variable takes 20 possible values over the range 0 to 1.00. The fees decision variable takes 100 possible values over the range 0 to 0.95, and quotas takes the same number of values between 0 and 0.52. The upper limits were determined by experiment, to ensure that optimal fees and quotas across all stock levels were not bounded by the upper limits, and that the upper limits were not greatly higher than the optimal levels.

Comparative results of fee and quota instruments are reported for 7 combinations of deterministic and stochastic settings of the stock, price and availability of fish.variables. The combinations are: 1) all variables deterministic; 2 to 4) one of the three variables stochastic; and 5 to 7) two of the three variables stochastic. The stochastic settings are summarised in Table 2. The additive stock stochastic term ε_x is normally distributed, and the multiplicative price and availability of fish stochastic terms (ε_p and ε_q) are lognormally distributed, using similar assumptions to those used in a previous model (Hannesson and Kennedy, 2003).
In calculating expected stage returns, three values of the stochastic term for each stochastic variable in a model run were used consistent with its distribution such that each value was equally likely.

Table 2: Standard deviations of variables

Variable	Variable distribution		Variable setting	
			Deterministic (D)	Stochastic (S)
Stock	Normal	σ_x	0.00	0.03
Price	Lognormal	σ_p	0.00	0.03
Availability of fish	Lognormal	σ_q	0.00	0.03

3.2 The recursive equations for fees and quotas as instruments

Consider first fees as the regulator's instrument. Let F denote the fee set per fish caught, so that the effective price of fish that fishers receive is $p-F$*, where p is the price of fish. The aim is to determine the optimal fee policy, specifying optimal F each possible current stock level, which holds for all future seasons. Here we are back to assuming that the problem is stationary in the sense that all stage functions are the same for all stages. The recursive functional equation for determining the optimal policy is*

$$V\{x\} = \max_{F\geq 0} \mathop{E}_{\varepsilon_x,\varepsilon_p,\varepsilon_q} \left[\pi\{x+\varepsilon_x, x+\varepsilon_x-\underline{x}\} + V\{\underline{x}+g\{\underline{x}\}\}/(1+r)\right]$$
$$\text{where } \underline{x} \text{ is end-of-season stock } = \begin{cases} c/((\overline{p}\varepsilon_p - F)\overline{q}\varepsilon_q & \text{if } x+\varepsilon_x \geq c/((\overline{p}\varepsilon_p - F)\overline{q}\varepsilon_q \\ x+\varepsilon_x & \text{otherwise} \end{cases} \tag{24}$$

The setting of *F* for any current *x* and stochastic effects for price and availability of fish determines the end-of-season stock. The end-of-season stock $\underline{x}$ targeted by rent-maximising open-access fishers is $c/((\overline{p}\varepsilon_p - F)\overline{q}\varepsilon_q$, which, unlike harvest, is independent of the current stock and of ε_x. However, this is subject to harvest being non-negative, or $x+\varepsilon_x \geq c/((\overline{p}\varepsilon_p - F)\overline{q}\varepsilon_q$.

Due to the stationarity assumption, the $V\{x\}$ state-value function is the same on both sides of equation (24), and the stage subscript can be dropped.

Turning to the regulator's other problem of finding the optimal quota policy, let *Q* denote the quota on the season's harvest, *H*. For any quota set, the harvest will equal the quota provided $x+\varepsilon_x \geq c/((\overline{p}\varepsilon_p - F)\overline{q}\varepsilon_q$; otherwise the harvest is the start-of-season stock less the targeted end-of-season stock, bounded by zero. The recursive functional equation for determining the optimal policy is

$$V\{x\} = \max_{Q \geq 0} \underset{\varepsilon_x,\varepsilon_p,\varepsilon_q}{E} \left[\pi\{x+\varepsilon_x, H\} + V\{x+\varepsilon_x - H + g\{x+\varepsilon_x - H\}\}/(1+r) \right] \tag{25}$$

$$\text{where } H = \begin{cases} Q & \text{if } \; x+\varepsilon_x - c/(\bar{p}\varepsilon_p\bar{q}\varepsilon_q) \geq Q \\ x+\varepsilon_x - c/(\bar{p}\varepsilon_p\bar{q}\varepsilon_q) & \text{if } \; 0 \leq x+\varepsilon_x - c/(\bar{p}\varepsilon_p\bar{q}\varepsilon_q) < Q \\ 0 & \text{otherwise} \end{cases}$$

Questions arise as to how the rate of discount r should be set, and how the relative performances of fees against quotas should be evaluated. Because the parameter values used in model runs are notional, an obvious non-arbitrary value for r is zero. For positive r, fees may be judged superior to quotas if $V\{x\}$ (the present value of rents to infinity from implementing the optimal policy to infinity) under fees is greater than $V\{x\}$ under quotas for all x. In the case of $r = 0$, the objective function is no longer the maximisation of $V\{x\}$ because the values of all policies may be infinite. Instead, the objective becomes maximisation of average expected stage return (see, e.g., Kennedy,1986).

In the results presented, a zero discount rate is used, and relative performance of optimal fees against optimal quotas is given by the relative average returns. This means that the recursive functional equations (24) and (25) are changed. The nature of the change is illustrated for a simplified version of equation(24), ignoring the inequality constraints, to give

$$V\{x\} + \gamma = \max_{F \geq 0} \underset{\varepsilon_x,\varepsilon_p,\varepsilon_q}{E} \left[\pi\{x+\varepsilon_x, x+\varepsilon_x - \underline{x}\} + V\{\underline{x} + g\{\underline{x}\}\} \right] \tag{26}$$

where γ is the average expected stage return, and $V_r\{x\}$ is a relative state-value function, giving the value of each state relative to the value zero for a reference state. Equation (25) is similarly modified to obtain the recursive functional equation for quotas with $r = 0$.

3.3 Results

The optimal fees and quotas for each of the 20 possible stock levels, and corresponding average stage returns, are shown in Table 3, for stock deterministic and stochastic. Solutions were obtained using the GPDP general purpose dynamic programming routines (Kennedy, 2003). Stock levels are after growth but before any stochastic stock effect. Fees shown for low stock levels for which zero harvest is optimal are the lowest fees. For these stock levels any higher fees would be equally optimal, for they too would ensure zero catch.

Table 3 shows a fee between 0.82 and 0.83 is optimal for all stock levels, and whether stock is deterministic or stochastic, except for low stock levels. Sensitivity analysis conducted using GPDP showed no difference in the average stage returns for the policy of fees equal to 0.82 for all stock levels.

Under quota management, the optimal quota does vary by start-of-season stock, and does depend on whether stock is stochastic. For both deterministic and stochastic stock, the optimal quota is zero for all start-of-season stocks lower than 0.42. For all stocks of 0.42 and higher, quotas under stochastic stock are higher than those under deterministic stock. These cater for the random positive stock effects, but at the expense of being lenient for the random negative stock effects. Overall, the average (expected) stage return is nearly 20 per cent lower than the maximum average stage return under fees.

Table 3: Optimal fee and quota policies for stock deterministic and stochastic

	Stock setting			
	Deterministic		Stochastic	
Stock *x*	Fee *F*	Quota *Q*	Fee *F*	Quota *Q*
0.00	0.00	0.00	0.70	0.00
0.08	0.00	0.00	0.76	0.00
0.15	0.36	0.00	0.80	0.00
0.23	0.56	0.00	0.83	0.00
0.29	0.66	0.00	0.83	0.00
0.36	0.73	0.00	0.83	0.00
0.42	0.77	0.00	0.83	0.00
0.49	0.80	0.00	0.83	0.00
0.54	0.82	0.02	0.83	0.04
0.60	0.82	0.07	0.83	0.09
0.65	0.82	0.12	0.83	0.15
0.70	0.82	0.17	0.83	0.20
0.75	0.82	0.22	0.83	0.25
0.79	0.82	0.26	0.83	0.29
0.83	0.82	0.30	0.83	0.33
0.87	0.82	0.34	0.83	0.37
0.91	0.82	0.38	0.83	0.40
0.94	0.82	0.41	0.83	0.44
0.97	0.82	0.44	0.83	0.47
1.00	0.82	0.47	0.83	0.50
Average stage return	0.103	0.103	0.101	0.084

The ratios of maximum average stage return under fees to that under quotas for all 7 experimental runs are shown in Table 4. Results for runs 1 and 2 have already been discussed.

Runs 3 to 5 all are for deterministic stock. In these cases, quotas perform better if price and availability are stochastic, singly or together. There is little difference in performance when the only stochastic effect is availability. Quotas perform significantly better than fees when price is stochastic (runs 3 and 5).

Results for runs 6 and 7 show that if stock is stochastic, fees still outperform quotas if either price or availability is stochastic.

Table 4: Relative performance of fees and quotas by stochastic effects

Run no.	Deterministic (D)/Stochastic (S)			Average Stage Return		
	Stock x	Price p	Availability q	Fees	Quotas	Fees/Quotas Ratio
1	D	D	D	0.1033	0.1034	1.00
2	S	D	D	0.1005	0.0835	1.20
3	D	S	D	0.0945	0.1092	0.87
4	D	D	S	0.1020	0.1029	0.99
5	D	S	S	0.0937	0.1087	0.86
6	S	S	D	0.0940	0.0884	1.06
7	S	D	S	0.0973	0.0830	1.17

The conclusion from these runs is that for the particular parameter values in this study, fees outperform quotas if there is a stochastic stock effect unknown to the regulator, whether or not price and availability are stochastic. On the other hand, if stock is deterministic, quotas perform at least as well as fees, whether or not price and availability are stochastic.

4. CONCLUSION

Important insights from the analysis are that fees have a comparative advantage over quotas when regulators and fishers have asymmetric information about start-of-season stock. The regulator can set a fee ensuring an efficient outcome, exploiting the myopic rent maximising behaviour of open-access fishers. The efficient fee does not depend on the start-of-season stock, whereas the efficient quota does. The efficient fee is the same for all start-of-season stocks and all seasons for problems which are stationary and have infinite policy stages. If the problem is not stationary, the efficient fee will generally differ by stage, but is dependent only on future parameters one stage into the future.

Results for the particular parameters used in this study indicate quotas outperform fees when there is no stock uncertainty. It remains to be investigated whether there is any generality in this result.

References

Hannesson, R. and Kennedy, J. (2003), "Landing Fees versus Fish Quotas", Working Paper A 27/2003, Norwegian School of Economics and Business Administration, Bergen.

Kennedy, J. O. S. (1986), *Dynamic programming: Applications to agriculture and natural resources*, Elsevier Applied Science, London.

Kennedy, J.O.S. (2003), General Purpose Dynamic Programming Manual, Department of Economics and Finance, La Trobe University, Melbourne. Online URL: http://www.business.latrobe.edu.au/staffhp/jkennedy/

Kennedy, J. and Hannesson R. (2003)., "Are within-season rents maximised in an open access fishery?" Working Paper A 36/2003, Centre for Fisheries Economics, Institute for Research in Economics and Business Administration, Bergen.

Weitzman, M. L. (2002), "Landing Fees vs Harvest Quotas with Uncertain Fish Stocks", *Journal of Environmental Economics and Management* 43, 325-338.