THE RELATIVE EFFICIENCY OF FEES AND QUOTAS APPLIED TO FISHERIES UNDER DIFFERENT TYPES OF UNCERTAINTY

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ABSTRACT

Quotas rather than landing fees are widely used for reducing the output of fisheries below open-access levels. One reason may be that quotas are perceived as a more reliable instrument for controlling total catch. However, whilst under certainty fees and quotas can be set each season to achieve the same target of total catch resulting in maximum rents over the long run, this need not apply under uncertainty. Weitzman has shown analytically that fees outperform quotas when the start-of-season stock is known by fishers but not by the regulator setting the landing fee or quota. It is difficult to obtain analytical results for other sources of uncertainty. Numerical optimisation is used for determining the preferred instrument for the typical simple characterisation of the fishery problem with stock, fish price and availability of the fish stock subject to the same type of asymmetric uncertainty for regulator and fisher as considered by Weitzman.

Keywords: Landing fees; quotas; uncertainty; numerical optimisation

INTRODUCTION

The fees placed on landed fish, or the quotas on catch, to impose in all future seasons on a fishery not subject to any uncertainty can be calculated to maximise the present value of economic rents, before charging for regulatory costs. Given that the present values would be the same for each instrument, the choice between 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 fisheries for which the profit from catching an additional unit of fish declines with decline in stock, and for which information about opening stock is asymmetric between the regulator and the fishers. 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 (2002, p. 338) has left the determination of the relative efficiency of the two output instruments in dealing with other sources of economic and ecological uncertainty as a future research agenda. Whereas an analytical approach can be taken when stock is uncertain, analytical approaches are more difficult for other sources of uncertainty. An analytical approach can be adopted for stock uncertainty under asymmetric information because end-of-season stock can be taken as the decision variable in the dynamic optimization problem, and its optimal setting can be independent of the start-of-season stock which is the state variable. Under specified conditions the optimal end-of-season stock can be achieved by setting a fee per unit of fish landed which is independent of the start-of-season stock, whereas this cannot be achieved by imposing any quota independent of the unknown start-of-season stock.

It appears that numerical approaches are required for investigating the situation for other sources of uncertainty. Hannesson and Kennedy (2003) have investigated these issues using a simulation model across wide ranges of parameters for distributions of the start-season-stock, price of fish, and availability of fish to capture, for alternative costs of fishing effort and stock exponents 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 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 a numerical optimising approach.

The aim of the paper 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 to society (inclusive of any revenue from fees paid by fishers). Which instrument results in the larger flow of rents over the long run? How does the comparative performance depend on which of the variables stock, price and availability to fishing are stochastic? Some answers are given to these questions for particular functions and parameter values, assuming that all stage functions are the same for all stages, and that the number of policy stages is infinite.

In the next section the fee and quota policy problems are specified and parameter values used in the numerical optimization runs are detailed. Results and conclusion sections follow.

PROBLEM DESCRIPTION

Function Specification

The growth function is

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

where a is the intrinsic growth rate and K is the carrying capacity of the environment. Growth occurs immediately after the season's harvesting is completed.

The instantaneous harvest function is

$$h = Eqx^b \tag{2}$$

where E is fishing effort, q is a measure of availability of fish to capture, and b is the stock exponent with range $0 \le b \le 1$. For $b = 1$, harvest is proportional to stock for any level of effort. For $b = 0$, harvest is independent of stock.

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

$$\overline{x}_{t+1} = \overline{x}_t - H_t + g_t\{\overline{x}_t - H_t\} + \varepsilon_{x,t} \quad \forall t \tag{3}$$

where H_t is harvest in season t and $\varepsilon_{x,t}$ is a random variable.

If c is the cost per unit of fishing effort, then the cost of catching one unit of fish for stock = x is $c/(qx^b)$. Rent for the season from harvesting stock down from start-of-season stock $\overline{x}_t$ to end-of-season stock $\underline{x}_t$ is

$$\pi\{\overline{x}, H\} = \int_{\underline{x}}^{\overline{x}} [p - c/(qz^b)]dz$$
$$= \begin{cases} p(\overline{x} - \underline{x}) - (c/q)[\ln(\overline{x}) - \ln(\underline{x})] & \text{for } b = 1 \\ p(\overline{x} - \underline{x}) - (c/q)\left[\overline{x}^{1-b} - \underline{x}^{1-b}\right]/(1-b) & \text{for } 0 \le b < 1 \end{cases} \tag{4}$$

where p is the price of fish and $H = \overline{x} - \underline{x}$. The season's rent is maximised by fishing down to $\underline{x}$ for which marginal rent is zero, or

$$p - c/(q\underline{x}^b) = 0 \tag{5}$$

resulting in

$$\underline{x} = (c/pq)^{1/b} \tag{6}$$

It is assumed that this is the end-of-season stock targeted in the unregulated open-access fishery.

Price is lognormally distributed, given by $p = \overline{p}\varepsilon_p$, where $\overline{p}$ is mean price and $\varepsilon_p = e^{v_p}$ with $v_p = \mathrm{N}(0, \sigma_p)$. Availability of the fish stock is also lognormally distributed, given similarly by $q = \overline{q}\varepsilon_q$.

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 $(p - F)$. The aim is to determine the optimal fee policy, specifying optimal F for each possible current stock level, which holds for infinite future seasons. To achieve this we assume 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

$$V\{\bar{x}\} = \max_{\min \bar{p}\varepsilon_p > F \geq 0} \; \underset{\varepsilon_x,\varepsilon_p,\varepsilon_q}{E} \left[\pi\{\bar{x}+\varepsilon_x, \bar{x}+\varepsilon_x - \underline{x}\} + V\{\underline{x} + g\{\underline{x}\}\}/(1+r) \right]$$

$$\text{where } \underline{x} = \begin{cases} (c/(\bar{p}\varepsilon_p - F)\bar{q}\varepsilon_q)^{1/b} & \text{if } \bar{x}+\varepsilon_x \geq (c/(\bar{p}\varepsilon_p - F)\bar{q}\varepsilon_q)^{1/b} \\ \bar{x}+\varepsilon_x & \text{otherwise} \end{cases} \tag{7}$$

and $V\{\bar{x}\}$ is the present value of rents from setting optimal fees at each of the infinite future decision stages, and r is an annual positive rate of discount (but see below for the need to replace equation (7) with equation (10) if $r = 0$). The setting of F for any current x and stochastic effects for price and availability of fish determines the end-of-season stock. The regulator is restricted to setting F so that net price to the fisher $(\bar{p}\varepsilon_p - F)$ must be positive for all ε_p. The end-of-season stock targeted by the open-access fishery regulated by fees is

$$\underline{x} = (c/(\bar{p}\varepsilon_p - F)\bar{q}\varepsilon_q)^{1/b} \tag{8}$$

which, unlike harvest, is independent of the current stock and of ε_x. However, this is subject to harvest being non-negative, or $\bar{x}+\varepsilon_x \geq (c/(\bar{p}\varepsilon_p - F)\bar{q}\varepsilon_q)^{1/b}$.

Due to the stationarity assumption, the $V\{\bar{x}\}$ state-value function is the same on both sides of equation (7), and no stage subscript is required.

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 the quota is less than the difference between the start-of-season stock and the unregulated open-access end-of-season stock (i.e. $Q \leq \bar{x}+\varepsilon_x - (c/(\bar{p}\varepsilon_p)\bar{q}\varepsilon_q)^{1/b}$); otherwise the harvest is less than Q, equal to the start-of-season stock less and the unregulated open-access end-of-season stock, bounded by zero. The recursive functional equation for determining the optimal policy is

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

$$\text{where } H = \begin{cases} Q & \text{if } \bar{x}+\varepsilon_x - (c/(\bar{p}\varepsilon_p\bar{q}\varepsilon_q))^{1/b} \geq Q \\ \bar{x}+\varepsilon_x - (c/(\bar{p}\varepsilon_p\bar{q}\varepsilon_q))^{1/b} & \text{if } 0 \leq \bar{x}+\varepsilon_x - (c/(\bar{p}\varepsilon_p\bar{q}\varepsilon_q))^{1/b} < Q \\ 0 & \text{otherwise} \end{cases} \tag{9}$$

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 $V\{\overline{x}\}$ (the present value of rents to infinity from implementing the optimal policy to infinity) under fees is greater than $V\{\overline{x}\}$ under quotas for all x. In the case of $r = 0$, the objective function is no longer the maximisation of $V\{\overline{x}\}$ because the values of all policies may be infinite. Instead, the objective becomes maximisation of expected average stage return (see, e.g., Kennedy, 1986).

In the results presented, a zero discount rate is used for base runs, and relative performance of optimal fees against optimal quotas is given by the relative average returns. This means that the recursive functional equations (7) and (9) are changed. The nature of the change is illustrated for a simplified version of equation (7), ignoring the inequality constraints, to give

$$V_r\{\overline{x}\} + \gamma = \max_{\min \overline{p}\varepsilon_p > F \geq 0} \; \underset{\varepsilon_x,\varepsilon_p,\varepsilon_q}{E} \left[\pi\{\overline{x}+\varepsilon_x, \overline{x}+\varepsilon_x - \underline{x}\} + V_r\{\underline{x} + g\{\underline{x}\}\} \right] \quad (10)$$

where γ is the expected average stage return, and $V_r\{\overline{x}\}$ is a relative state-value function, giving the value of each state relative to the value zero for one arbitrarily selected reference state. Equation (9) is similarly modified to obtain the recursive functional equation for quotas with $r = 0$.

Parameter Values and Solution Details

The values of parameters in functions (1) to (3) are given in Table 1, and the standard deviations for stochastic variables in Table 2.

Table 1: Parameter values*

Parameter		Value
Mean price of fish	$\overline{p}$	**1**
Mean availability of fish	$\overline{q}$	**1**
Cost per unit of fishing effort	c	**0.1**, 0.9
Stock exponent	b	**1,** 0.1
Intrinsic growth rate	a	**0.5**
Carrying capacity	K	**1**
Rate of discount	r	**0**, 0.05, 0.1

*Base run values in bold

Table 2: Standard deviations of variables

Variable	Variable distribution		Standard deviation setting	
			Deterministic (D)	Stochastic (S)
Stock	Normal	σ_x	0	0.3
Price	Lognormal	σ_p	0	0.1, 0.3, 0.5
Availability of fish	Lognormal	σ_q	0	0.1, 0.3, 0.5

Solutions are obtained numerically. The start-of-season stock state variable takes 20 possible values over the range 0 to 1.00. The fee decision variable takes 100 possible values over the range 0 to 0.95, and the quota decision variable takes 100 values between 0 and 0.52. The optimal $V\{\bar{x}\}$ stock values for $\bar{x}$ falling between the 20 defined stock values are estimated by linear interpolation. The upper limits on the decision variables 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.

In calculating expected stage returns and determining optimal decisions, three values of the stochastic term for each stochastic variable in a model run were used: the mean, and one value below and another above the mean, consistent with the variable's probability distribution, and each value being equally likely. Thus in a run with positive standard deviations for all three variables in Table 2, equation (7) is evaluated 27 times for each value of the state variable and the regulator's fee (and equation (9) similarly for quota settings).

RESULTS

The optimal fees and quotas for each of the 20 possible start-of-season stock levels, and corresponding average stage returns, are shown in Table 3, for two scenarios both with price and availability fixed: stock deterministic (run 1) and stochastic (run 2). Solutions were obtained using the GPDP general purpose dynamic programming routines (Kennedy, 2003). Stock levels are 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 varies 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 expected average stage return under quotas is nearly 20 per cent lower than the expected average stage return under fees.

The results are consistent with the analytical results obtained by Weitzman (2002). For start-of-season stock unknown to the regulator but known to fishers, the fee which maximizes efficiency is not dependent on the start-of-season stock, and gives higher returns than optimal quotas set before knowing the stochastic stock event.

The ratios of maximum average stage return under fees to that under quotas for eight experimental runs, including runs 1 and 2, are shown in Table 4 for stock exponent $b = 1$. Runs 3 to 5 all are for deterministic stock. In these cases, quotas perform better for price and availability 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 to 8 show that, for the selected standard deviations, if stock is stochastic, fees still outperform quotas if price, availability, or both are stochastic. If price is stochastic, fee regulation is only marginally ahead.

Table 3: Optimal fee and quota policies for stock deterministic ($\sigma_x = 0$) and stochastic ($\sigma_x = 0.3$)[*]

	Regulator's initial-stock information			
	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	0.35	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	0.04
0.42	0.77	0.00	0.83	0.11
0.49	0.80	0.00	0.83	0.17
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	0.35	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

[*]Other parameter settings are $\sigma_p = 0$, $\sigma_q = 0$, $b = 1$, $c = 0.1$, $r = 0$

Table 4: Relative performance* of fees and quotas by stochastic effects for stock exponent *b* = 1

Run no.	Standard deviations			Average stage return		
	x	*p*	*q*	Fees	Quotas	F/Q
1) DDD	0	0	0	0.1033	0.1034	0.999
2) SDD	0.3	0	0	0.1006	0.0840	1.198
3) DSD	0	0.3	0	0.0946	0.1093	0.865
4) DDS	0	0	0.3	0.1020	0.1028	0.992
5) DSS	0	0.3	0.3	0.0937	0.1088	0.862
6) SSD	0.3	0.3	0	0.0944	0.0894	1.056
7) SDS	0.3	0	0.3	0.0975	0.0835	1.168
8) SSS	0.3	0.3	0.3	0.0942	0.0892	1.057

*Other parameter settings are $c = 0.1$, $r = 0$.

The effect of switching the stock exponent from one to much less than one ($b = 0.1$) is shown in Table 5. For cases where stock is deterministic and price is stochastic (runs 3 and 5), the expected average stage return under fee regulation virtually collapses, whereas under quota regulation it increases slightly. Consequently, the relative performance of quota regulation increases substantially. The reason for this relates to the discussion below of the implications of stock versus price uncertainty for the more efficient control instrument. Overall, for all cases of uncertainty (runs 2 to 8), the relative performance of fees declines.

Table 5: Relative performance* of fees and quotas by stochastic effects for stock exponent *b* = 0.1

Run no.	Standard deviations			Average stage return		
	x	*p*	*q*	Fees	Quotas	F/Q
1) DDD	0	0	0	0.1114	0.1115	0.999
2) SDD	0.3	0	0	0.1030	0.0988	1.043
3) DSD	0	0.3	0	0.0001	0.1174	0.001
4) DDS	0	0	0.3	0.0942	0.1112	0.847
5) DSS	0	0.3	0.3	0.0001	0.1171	0.001
6) SSD	0.3	0.3	0	0.1016	0.1041	0.976
7) SDS	0.3	0	0.3	0.1001	0.0985	1.017
8) SSS	0.3	0.3	0.3	0.1013	0.1038	0.976

*Other parameter settings are $c = 0.1$, $r = 0$.

Equation (6) shows the unregulated open-access end-of-season stock to be $\underline{x} = (c/\overline{p}\varepsilon_p\overline{q}\varepsilon_q)^{1/b}$, and equation (8) that it is $\underline{x} = (c/(\overline{p}\varepsilon_p - F)\overline{q}\varepsilon_q)^{1/b}$ under fee regulation. The target end-of-season stock depends on the product of the net price of fish for fishers and availability. Does it follow that variability in p and variability in q will have similar effects on the relative performance of fee and quota regulation? Equation (4) shows that for $F=0$, the same changes in p and q have different effects on the season's rent, which suggests it will not. A stochastic ε_p which doubles p will double revenue for the same harvest, but harvest increases because $\underline{x}$ is halved. A stochastic ε_q which doubles q will also halve $\underline{x}$ but without any immediate effect on revenue. This suggests that the change in the regulated end-of-season stock will be more variable for a given proportional change in p than for the same proportional change in q. It is likely that fee regulation will perform relatively worse than quota regulation for p stochastic through the value of F set at the start of the season on the basis of expected price being unresponsive to realized price.

Further, it can be seen from that under fees, if q is fixed and p is stochastic, the target end-of-season stock for any set F will vary with price. For the same proportional variability in p and q, the variability in the target end-of-season stock is greater than for the case of p fixed and q stochastic the larger F is compared to p. Again this suggests that fees will perform relatively worse as variability in p increases compared to increased in variability in q.

The effect on the relative performance for the example problem of increasing the variability of p for q deterministic, and the variability of q for p deterministic, is shown in Table 6 for the case of stock deterministic. Results are largely consistent with expectations. For increases in standard deviations from 0.3 to 0.5, the relative performance of fees falls at a substantially greater rate for price variability than for availability variability. This effect is much greater for $b=0.1$ compared to $b=1$. It is noticeable that fees and quotas perform much the same as variability in q increases when it is the only source of variability.

Table 6: Ratio of net returns* from fee regulation to quota regulation by stock exponent (*b*)

Run	Standard deviations			Stock exponent b	
no.	x	p	q	1	0.1
1) DDD	0	0	0	0.999	0.999
2) DSD	0	0.1	0	0.999	0.999
3) DSD	0	0.3	0	0.865	0.001
4) DSD	0	0.5	0	0.614	0.001
5) DDS	0	0	0.1	0.996	0.880
6) DDS	0	0	0.3	0.992	0.847
7) DDS	0	0	0.5	0.995	0.785

*Other parameter settings are $c = 0.1$, $r = 0$.

To test whether the results of the relative performance of fees and quotas still hold for likely positive rates of discount, optimal fee and quota settings and corresponding expected present values over infinite periods were determined for rates of 5 and 10 per cent. The expected present values were determined as the sum of the product of the expected present value of each of the 20 stock states $(V\{\bar{x}\})$ and the long-run probability of the state under the optimal policy applied over infinite periods. Results in Table 7 for the three discount rates can be compared for the cases of runs 1 to 3 in Table 4. The ranking of fee to quota regulation is preserved. However for the cases of stock stochastic (run 2) and price stochastic (run 3), Table 7 shows a tendency for the relative advantage to decline as the rate of discount is increased.

Table 7: Ratio of net returns* from fee regulation to quota regulation by rate of discount (b = 1, c = 0.1)

Run	Standard deviations			Rate of discount per period		
no.	x	p	q	0%	5%	10%
1) DDD	0	0	0	0.999	0.997	0.998
2) SDD	0.3	0	0	1.198	1.190	1.177
3) DSD	0	0.3	0	0.865	0.875	0.887

*Average stage return for r = 0%, and expected present value over infinite periods for r = 5 and 10 %

A case can be made for there being an approximate complementarity condition between the relative performance of price and quantity instruments, and price and quantity sources of uncertainty. The condition can be stated as: if the source of uncertainty for the regulator is stock at the time of control setting, then fees are the more efficient control instrument; if the source of uncertainty for the regulator is price at the time of control setting, then quotas are the more efficient control instrument. The first part has been argued by Weitzman (2002), for a situation in which price is certain, and ensures an efficient outcome for any initial stock even though the regulator does not know what it is. The second part applies in a situation in which initial stock is certain. Here fees are likely to be more efficient. If the season's price turns out to be higher than the regulator's initial expectation, end stock will not fall below the regulator's target end stock under quota regulation. Under fees it will. It is true that if the realized price is higher than expected, it *would be* more efficient to target a lower season end stock than is optimal for expected price. However, under fees the season end stock will not take account of expected future price, whereas under quotas, although the harvest will be too low, the season end stock will take account of expected future price.

In the special case of the cost per unit of fishing effort (c) equal to zero, it is clear from equation (8) that fee regulation cannot be used to raise the fishery end stock above the unregulated open access level (zero in this case), whether or not there is any source of uncertainty. This contrasts with quota regulation. The same issue arises if $b = 0$. However, neither case contradicts Weitzman's result because these cases do not allow marginal rent from catching an additional unit of fish to decline as stock declines.

The complementarity condition just outlined is only a hypothesis. It may be possible to prove it analytically for certain cases. Empirical results are reported here for particular parameters for a typical simple characterisation of the fishery problem. Results consistent with the condition can be seen in the results for runs 2 and 3 in Table 4, and are shown again in Table 8 under runs 1 and 2. They are compared with outcomes for runs 3 and 4, for which the cost per unit of fishing effort is increased from 0.1 to 0.9. This increases the variability of the margin ($p - c$) when p is stochastic. Also equation (8) implies the target end-of-season stock under fees is more variable under price uncertainty for higher *c*. Does this make control by fees more difficult than control by quotas under price uncertainty? For the example problem it does.

Table 8: Relative performance* of fees and quotas for only stock stochastic and only price stochastic, for low (c = 0.1) and high (c = 0.9) effort costs

Run	Standard deviations				Average stage return		
no.	x	p	q	c	Fees	Quotas	F/Q
1) Stock S	0.3	0	0	0.1	0.1006	0.0840	1.198
2) Price S	0	0.3	0	0.1	0.0946	0.1093	0.865
3) Stock S	0.3	0	0	0.9	0.0128	0.0122	1.047
4) Price S	0	0.3	0	0.9	0.0033	0.0178	0.188

*Other parameter settings are b = 1, r = 0.

CONCLUSION

The numerical results are consistent with Weitzman's (2002) result that if start-of-season stock is uncertain for the regulator at the time that the fee or quota must be set, but that fishers know stock with certainty as they fish, fee regulation outperforms quota regulation. He referred to the type of uncertainty he addressed as ecological uncertainty, and left open the research project of determining the comparative advantage of fees over quotas for other types of ecological and economic uncertainty.

In this study the relative performance of fees versus quotas was examined for different combinations and levels of stock, price and availability uncertainty for the regulator but not the fisher. The main result is that quotas outperform fees in the presence of price uncertainty and the absence of stock uncertainty. No rules were found for choosing between fee and quota regulation when both uncertainties are present. Uncertainty about the availability of the fish stock has a lower impact than price uncertainty. Preferences tend to shift in favour of quotas for a higher effort cost and a lower stock exponent.

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