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Rethinking Property Rights - Introducing Expected Quotas for Fisheries Management Under Uncertainty

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This paper proposes a new management tool called expected quotas. Each fisher is penalized if he goes beyond and rewarded if he goes below an allocated quota. The penalty is costlier than the reward. Dynamic programming calculations with uncertainties in the stock abundance estimate and fishermen s costs indicate that compared to regimes with fixed quotas, the use of expected quotas causes a substantial increase in the value of the fishery and reduces the risk of resource collapse. An efficient distribution of expected quotas is insured through a market-based system similar to the Individual Transferable Quota (ITQ) system.

1. INTRODUCTION

Total Allowable Catch (TAC) is a concept that has been in use since the early history of fisheries management. It fixes an upper limit for exploitation of a species in a resource pool over a regulation period and is fixed, for instance, in negotiations between nations that share a common resource pool.

The traditional strategy in fisheries regulation to achieve TAC has been to restrict fishing effort by administrative decrees: limiting days at sea; closed areas; and, closed seasons. Experience has shown that this type of regulation can be very wasteful because the "race for fish" encourages excess investment to increase hauling capacity, thereby ultimately generating higher costs.

Management regimes based on establishing private property rights over shares of TAC (individual fixed quotas) in fisheries are considered a more efficient way to implement regulation because the "race" will vanish when each fisherman has his own share of the fishing to worry about. Moreover, by making these rights marketable, refereed to as Individual Transferable Quotas (ITQs), an efficient allocation among fishers is possible. However, a big problem that remains is the high uncertainty in estimates that are used as basis for a proper TAC setting. Not only is there uncertainty in measurements performed by stock surveys before the TAC is determined. Also, as a result of a naturally fluctuating resource, there is additional uncertainty on what is important for future exploitation; the spawning stock condition after harvesting of the TAC determined amount.

Arnason [1] points out another source of non-efficiency with ITQs. With finite regulation periods, different exploitation paths within the period will satisfy the quota constraint; but generally, not all these paths are optimal. He proposes a continuous quota system where the quotas are permanent shares of a total allowable rate of catch and transferable on a market. The problems above can then be solved with the Minimum Information Management (MIM) scheme where essentially the regulator only needs to monitor the quota share price and to adjust total catch rate until the total value of the share quotas is maximized. The efficiency of this system depends on the assumption that the expectations of the fishers are the best available predictor of future conditions in the fishery.

This article proposes a new quota method, the Individual Transferable Expected Quota (ITEQ) system, which applies the idea Arnason uses when it comes to exploiting the individual fishers as a source for the best information available, but the quota form does not have to be continuous. However, as the naming of the system implies, the type of quotas (or property rights) issued and traded here are in quantities that are expected by the regulator and not fixed as is the case with Arnasons proposal and the ordinary ITQ system.

In section 2 I explain the basics of the individual expected quota (EQ) system and argue why management problems are better handled there. By means of dynamic programming, section 3 compares the fixed quota (FQ) and expected quota (EQ) systems in cases where there is uncertainty in stock assessment and fishermen's costs. Section 4 expels the formulation needed when EQs are allowed to be marketable.

2. THE INDIVIDUAL EXPECTED QUOTA SYSTEM

In the individual expected quota (EQ) system, the regulator, instead of allocating an individually fixed quota (FQ), allocates what he expects the individual catch realizations to be in the form of an individually expected quota (EQ). Instead of determining a Total Allowable Catch (TAC), he determines what I call a Total Allowable Expected Catch (TAEC): the sum of all fishermen's allocated EQs. As the fixed quota (FQ) is a private property right under a TAC umbrella, the EQ corresponds to a private property right under the TAEC umbrella.

The allocation of EQs implies that each fisherman must sign a contract, which allows him to exceed the allocated quota. If he does however, he will be obligated to pay a penalty. On the other hand, if he catches less then the quota, he will receive a reward. The idea now is to set the amounts in the penalty/reward scheme in a way that induce "selfish" fishermen to behave in a socially optimal way.

One necessity for such a scheme is that the penalty for going over the quota by a certain amount is higher than the reward paid for going under by the same quantity. This is explained by the fact that the negative externality the fisher levies to the other fishers in case of exceeding the quota is higher than the positive externality he grants by going below the quota. The effect of this penalty/reward rule is to raise the marginal cost for the fisherman with the catch he accumulates through the year. Due to this, the fisherman's catch will eventually be lessened because sooner or later his vessel will gather a catch that makes his total marginal costs equal to the fish price which again means that additional catch will be unprofitable. From the regulator's point of view, and with the information he possesses, this is the expected catch for the vessel allocated this quota while TAEC is the expected total catch of the fishery.

Consider the optimal continuous share quota system Arnason [1] describes where shares of catch rate quotas are tradable on a perfect market and where the Minimum Information Management scheme prescribes the regulator to adjusts total catch rate quota continuously and without compensation based on observation of the quota share price. Then, imagine no other changes except that the catch rate quotas he uses is exchanged with expected catch rate quotas. Provided all expectations are fulfilled, the system obviously resembles Arnason's design. The necessary conditions to resolve such a continuous expected quota system are derived in appendix A and it is shown that the optimal penalty/reward scheme is in fact an non-linear Pigouvian tax individualized by the quota trade. To find it, however, requires information on each fisher's cost and harvesting functions and is an exercise clearly beyond reach.

A first step in a more useful approach is to add the quite realistic assumption that individual fishers ignores their own influence of the stock condition because then it would be possible to calculate a second best optimal penalty/reward scheme with information requirements limited to the aggregated measures of the fishery. Such a scheme equate the current shadow value of the resource along the optimal path and exhibits a form with a time varying total expected quota parameter.

The second step is to freeze the adjustments of the total expected allowable catch rate over a regulation period which is equivalent to a discrete individual transferable expected quota (ITEQ) system where the quantity is the added expected catch rate (aggregated catch) and the optimal scheme is determined by added marginal profit streams. If total actual catch rate deviates from the optimal one, it will be reflected both in the observation that it actually deviates and in the price of the expected quota share. Due to the reward everybody receives, the price will be higher if the operating point is below expected quota and vice versa. The corresponding procedure to Arnason's minimum management program is then for the regulator within the regulation period to buy/sell quotas with the goal to equate total actual catch rate and total expected quota rate. This is a correction of quotas with compensation. Further, at the beginning of each regulation period, regulator follows Arnason procedure directly and adjusts total quota without compensation to a level that maximizes the value of the fishery eventually also combined with estimates from stock assessments. Provided that a fisher is rational and know his profit stream at every point in time until the end of the regulation period, he will with this procedure follow the socially optimal catch rate path.

If the fisher only roughly predicts his stream of profit and what catch he ends up with and/or if the penalty/reward scheme is not optimal, the result is that the point of time when he decides to stop fishing will be at the end of the regulation period. This is however still an advantageous prospect because his actual catch will thereby be influenced by the current stock size at that point in time and his costs without the penalty/reward depend on fish availability. In reality, with the model in use here, it ends up with being the mean actual stock size over the year that determines his catch. Then, when we sum up all fishermen's catches, we see that this effectively can reduce uncertainties about future recruitment of the fishery compared to the TAC-FQ system where total actual catch is predetermined at the beginning of the regulation period. Hence, as the results in section 3 indicate the method increases the economic value of the fisheries and reduce the risk of resource collapse compared to harvesting with fixed quotas. Because it is the mean stock size over the year that determines actual catch, a conjecture might be that human activity with this system could act as a negative feedback on natural fluctuations[1] as opposed to a fixed quota regime that usually reduces population stability (Beddington and May [2]).

It is natural to separate the calculation of the penalty/reward scheme into two components; a subsidy and a progressive tax. An "exact catch budget" for the fishing authorities would emerge if all fishermen were to fill their EQs exactly. The subsidy and the tax needed to keep status quo for the income of the fishermen in this case is determined by the condition that the "exact catch budget" equals *zero*. Nevertheless the regulator's expected budget will be positive simply because the regulating authorities penalize more for going over the quota with a certain quantity than they give back as a reward for going under the quota with the same quantity[2]. This might, from the fishing industry's point of view, be considered as an acceptable way for the authorities to confiscate some of the resource rent because it is the fishermen themselves that eventually choose to exceed the quota and it is the authorities that take the risk and have to pay if the stock size is overestimated.

The subsidy part of the penalty/reward scheme must be distributed in such a way that the participants do not abandon the fishery without reporting it. For example if some of the subsidy is given in form of cash it would be tempting for someone already planning to stop fishing to simply sign on and receive the subsidy. The subsidy should therefore be in the form of a price subsidy. Calculations ahead show that it is optimal to keep the price subsidy as low as possible. Public taxation of the industry could therefore favorably be realized as a partly refrained price subsidy.

A considerable effort lies behind finding a form of the penalty function that would be optimal. So for sake of simplicity, not at least for the fishermen who should be able to do their own calculations with this penalty/reward scheme, I choose a quadratic EQ-system which also can be looked upon as a second order approximation of the optimal scheme. Here the regulator imposes fisherman *i* in year *k* a price subsidy $a_{1,k}H_k^i$ and a quadratic penalty function chosen to

[1] The proof of this conjecture might involve major mathematical difficulties.

[2] The figures d) in section 3 displays numerical examples of the expected budget as a function of expected recruitment.

be of the form $\frac{a_{2,k}}{2d_k^i}\left(H_k^i\right)^2$ where H_k^i is fisherman's accumulated harvest through the year and d_k^i is the fisherman's allotted share (division) of the total catch H_k. That is, we have the relationships; $H_k^i = d_k^i H_k$ and $\sum_i d_k^i = 1$.

Assume that fishers are not in collaboration with or vertically integrated to the processing industry and that fishers have a profit-maximizing behavior, except that they do not consider their influence on stock size when they maximize their profit. Since the fishermen consider stock size as static and they take the decision about when to stop fishing at the end of the year, it is the stock size at this time that determines what they view as their costs. Thus, omitting fixed costs, the profit function of year *k* that fisher *i* is maximizing is given by

$$\gamma_k^i = \left(p + a_{1,k}\right)H_k^i - \frac{a_{2,k}}{2d_k^i}\left(H_k^i\right)^2 - C^i\left(e_{k+1}^i\right) \tag{2.1}$$

where *p* is the (assumed constant) first-hand price for the fish and where $C^i\left(e_{k+1}^i\right)$ is assumed to be an increasing cost as a function of the effort rate evaluated at the end of the year.

Assume a standard (Schaefer) fishery production function where effort rate is scaled such that the harvest rate is

$$h^i = x e^i \tag{2.2}$$

where *x* is the stock size.

It is trivial to prove that an increasing cost (and we can include linear cost as a limiting case) as a function of effort rate means that it under certain conditions is optimal for the fisherman to perform a constant effort rate through the year. Using this when integrating (2.2) on both sides from *k* to *k*+1 gives a relationship between accumulated harvest H_k^i and accumulated effort E_k^i which is

$$H_k^i = \bar{x}_k E_k^i \tag{2.3}$$

where $\bar{x}_k$ by definition is the mean stock size over the year and here assumed equal to

$$\bar{x}_k = \frac{x_k + x_{k+1}}{2} \tag{2.4}$$

With this scaling we can set $e_{k+1}^i = E_k^i$ and replace the variable of the cost function in equation (2.1) with one that depends on H_k^i. That is, the profit function (2.1) becomes

$$\gamma_k^i = \left(p + a_{1,k}\right)H_k^i - \frac{a_{2,k}}{2d_k^i}\left(H_k^i\right)^2 - C^i\left(\frac{H_k^i}{\bar{x}_k}\right) \tag{2.5}$$

Assuming a perfect distribution of EQs, all fishermen and the whole fishery will have the same marginal costs. We can then, in the following, set $d_k^i = 1$ and omit the *i* index to indicate the aggregated variables. For simplicity, we assume that the cost function is linear w.r.t. the effort rate. Then, with the production function we use (equation (2.2)), the marginal cost of harvest $C_H(x)$ is of the form

$$C_H(x) = \frac{c}{x} \tag{2.6}$$

where c is the constant cost of unit effort. The aggregated profit function of year k that is maximized by the fishers, when fixed costs is disregarded, is given by

$$\gamma_k = \left(p + a_{1,k}\right)H_k - \tfrac{1}{2}a_{2,k}H_k^2 - \frac{c}{\overline{x}_k}H_k \tag{2.7}$$

The inner solution of the maximization of equation (2.7) w.r.t. total harvest is

$$H_k = \frac{\left(p + a_{1,k}\right)\overline{x}_k - c}{a_{2,k}\overline{x}_k} \tag{2.8}$$

If we assume that the harvest H_k is always taken except that there will always be a minimum $\underline{s}$ left from the stock that escapes from harvesting, the limitations $0 \le H_k \le x_k - \underline{s}$ apply here and (2.8) is changed to

$$H_k = H_k\left(x_k, x_{k+1}, c\right) = \max\left(0, \min\left(x_k - \underline{s}, \frac{\left(p + a_{1,k}\right)\overline{x}_k - c}{a_{2,k}\overline{x}_k}\right)\right) \tag{2.9}$$

In addition the fishermen need a positive profit to be willing to join the fishery (sign the contract). That is, they plan a harvest $\hat{H}_k$ that might be different from the catch H_k they end up with because the decision about this is made at the beginning of the regulation period when what they consider as their costs is determined by the present time stock size x_k. Thus the profit function (still neglecting fixed costs) for this decision is

$$\hat{\gamma}_k = \left(p + a_{1,k}\right)\hat{H}_k - \tfrac{1}{2}a_{2,k}\hat{H}_k^2 - \frac{c}{x_k}\hat{H}_k \tag{2.10}$$

from which the planned harvest (with restriction $\hat{H}_k \ge 0$) is calculated to

$$\hat{H}_k = \max\left(0, \frac{\left(p + a_{1,k}\right)x_k - c}{a_{2,k}x_k}\right) \tag{2.11}$$

With the above restriction and (2.9) we find that the actual harvest the profit maximizing skippers will go for, is

$$H_k = H_k\left(x_k, x_{k+1}, c\right) = \begin{cases} 0 & \text{if } \hat{\gamma}_k < 0 \\ \max\left(0, \min\left(x_k - \underline{s}, \frac{\left(p + a_{1,k}\right)\overline{x}_k - c}{a_{2,k}\overline{x}_k}\right)\right) & \text{else} \end{cases} \tag{2.12}$$

Regulation adjustments, which are to instill parameters $a_{1,k}$ and $a_{2,k}$, take place at the start of each quota year $k = \{1,2,3,.........\}$. These adjustments are based on the presumption of a *zero* “exact catch budget” as mentioned above, the decision of what the expected total catch (TAEC) should be and the estimation of marginal aggregated cost for the fishery. This subject will be addressed in the next section.

3. DETERMINING THE OPTIMAL TOTAL ALLOWABLE EXPECTED CATCH

The aim of this section is to determine the optimal parameters of the EQ system and to compare the result with the optimal solution for fixed quotas (FQs). The results are presented at the end of the section as numerical examples. First the necessary equations used to form the numerical results are ascertained.

Assume that the basic resource model (Reed [8]) is given by:

$$\begin{aligned} x_{k+1} &= z_{k+1}G(s_k) \\ s_k &= x_k - H_k \end{aligned} \tag{3.1}$$

where x_k denotes the stock level (recruits), at the beginning of the k th year, H_k is harvest through year k and s_k denotes escapement at the end of that year. The average stock-recruitment relationship is multiplied by the random factor z_k. These random variables are assumed independent and identically distributed with density function $f_{z_k}(z_k) = f_z(z)$ with mean $\bar{z} = 1$ for $k = \{1,2,3,.........\}$. Also, assume that the escapement level s_k is known exactly and that c, cost of unit effort in equation (2.6), is uncertain with density function $f_c(c)$ with mean $\bar{c}$.

Let $x_{k+1}(z_{k+1}, x_k, c)$ denote the solution w.r.t. the future stock size x_{k+1} of the implicit equation

$$x_{k+1} = z_{k+1}G(s_k) = z_{k+1}G\big(x_k - H_k(x_k, x_{k+1}, c)\big) \tag{3.2}$$

Thus, harvest in equation (2.12) can be written as

$$H_k = H_k\big(x_k, x_{k+1}(z_{k+1}, x_k, c), c\big) = H_k(z_{k+1}, x_k, c) \tag{3.3}$$

Let $a_{1,k}$ and $a_{2,k}$ denote the set of regulation parameters for year k and let $H_k(z_{k+1}, x_k, c, a_{1,k}, a_{2,k})$ denote the realized harvest when these are used. Expected harvest $\overline{H}_k = \overline{H}_k(s_{k-1}, a_{1,k}, a_{2,k})$ when last year's escapement s_{k-1} is known and the regulation parameters is given is defined as the <u>Total Allowable Expected Catch (TAEC)</u> and is given by

$$\overline{H}_k = E\left\{H_k(z_{k+1}, x_k, c, a_{1,k}, a_{2,k}) \middle| s_{k-1}\right\} = E_c E_{z_{k+1}} E_{z_k}\left\{H_k\big(z_{k+1}, z_k G(s_{k-1}), c, a_{1,k}, a_{2,k}\big)\right\} \tag{3.4}$$

As noted in the above section, we assume the price subsidy parameter $a_{1,k}$, when $a_{2,k}$ and s_{k-1} are given, to be determined so that the “exact catch budget” for the regulating authorities is *zero*. The “exact catch budget” for year *k* is symbolically denoted $B_k(\overline{H}_k)$ and is given by

$$B_k(\overline{H}_k) = E\left\{B_k \middle| H_k^i = E(H_k^i) \text{ for all } i\right\} = \tfrac{1}{2}a_{2,k}\left[\overline{H}_k(s_{k-1}, a_{1,k}, a_{2,k})\right]^2 - a_{1,k}\overline{H}_k(s_{k-1}, a_{1,k}, a_{2,k}) \tag{3.5}$$

The solution of $a_{1,k}$ is then found through the implicit equation $B_k\left(\overline{H}_k\right)=0$. Hence, using this solution, the realized harvest $H_k\left(z_{k+1},x_k,c,a_{2,k}\right)=H_k\left(z_{k+1},x_k,c,a_{1,k}\left(a_{2,k}\right),a_{2,k}\right)$ will depend on the regulation parameter $a_{2,k}$ only. This regulation parameter will be used as the control variable in the Dynamic Programming formulation that follows.

Let π_k denote social economic revenue of year *k* given by

$$\pi_k=\pi_k\left(x_k,H_k\right)=pH_k-\int_{x_k-H_k}^{x_k}C_H(x)dx=pH_k-c\ln\left(\frac{x_k}{x_k-H_k}\right) \tag{3.6}$$

Consider the optimization criteria to maximize expected present value of economic rents:

$$\max E\left\{\sum_{k=1}^{\infty}\alpha^{k-1}\pi_k\right\} \tag{3.7}$$

where α denotes the discount factor, $0<\alpha\le 1$.

The optimal present value function $V^*\left(s_0\right)$ satisfies the Bellman functional equation of Dynamic Programming

$$V^*\left(s_0\right)=\max_{a_{2,1}}E\left\{\pi_1+\alpha V^*\left(s_1|s_0\right)\right\}=\max_{a_{2,1}}E\left\{\pi_1+\alpha V^*\left(x_1-H_1\left(z_2,x_1,c,a_{2,1}\right)|s_0\right)\right\}$$

$$=\max_{a_{2,1}}\left[E_cE_{x_1}E_{z_2}\left\{pH_1\left(z_2,x_1,c,a_{2,1}\right)-c\ln\left(\frac{x_1}{x_1-H_1\left(z_2,x_1,c,a_{2,1}\right)}\right)\right\}\right. \tag{3.8}$$

$$\left.+\alpha E_cE_{z_1}E_{z_2}\left\{V^*\left(z_1G\left(s_0\right)-H_1\left(z_2,z_1G\left(s_0\right),c,a_{2,1}\right)\right)\right\}\right]$$

Calculation of the expectation in this case incorporates integration both over the density function for z_1, z_2, c, and x_1. The function $V^*\left(s_0\right)$ and the associated regulation parameter $a_{2,k}$ are found by inserting a trial function for $V^*\left(s_1\right)$ and by doing repetitive evaluations of (3.8).

The probability density function for x_1 given s_0, $f_{x_1}\left(x_1\right)$, is needed for calculation of (3.8). It is given by

$$f_{x_1}\left(x_1\right)=\frac{1}{G\left(s_0\right)}f_{z_1}\left(\frac{x_1}{G\left(s_0\right)}\right) \tag{3.9}$$

In the examples to follow, the probability distribution function for x_2, the stock size after harvesting is used in the calculations. The probability distribution function for x_2 when *c* is fixed is

$$f_{x_2}\left(x_2\right)=\int_0^{\infty}f_{x_2|x_1}\left(x_1,x_2\right)f_{x_1}\left(x_1\right)dx_1 \text{ where } f_{x_2|x_1}\left(x_1,x_2\right)=\frac{dz_2\left(x_1,x_2\right)}{dx_2}f_{z_2}\left(z_2\left(x_1,x_2\right)\right) \tag{3.10}$$

where $z_2(x_1,x_2)$ is the solution w.r.t. z_2 in equation (3.2) when k = 1. Using this, we find that the probability distribution function for x_2 when cost of unit effort c is uncertain is given by

$$f_{x_2}(x_2) = \int_0^\infty f_{x_2|c}(x_2,c)\, f_c(c)dc \tag{3.11}$$

where $f_{x_1|c}(x_2,c) = f_{x_2}(x_2)$ in (3.10).

The optimal expected escapement is also displayed. It is given by

$$E\{s_1^*|s_0\} = E_c E_{z_2} E_{z_1}\{\max(\underline{x}, z_1 G(s_0) - H_1(z_2, z_1 G(s_0), c, a_2^*))\} \tag{3.12}$$

And likewise, the expected budget for the EQ system is given by

$$\overline{B}_1 = E\{B_1|s_0\} = E_c E_{z_1} E_{z_2}\left\{\tfrac{1}{2}a_{2,1}H_1^2(z_2, z_1G(s_0), c, a_{2,1}) - a_{1,1}(a_{2,1})H_1(z_2, z_1G(s_0), c, a_{2,1})\right\} \tag{3.13}$$

A similar Dynamic Programming equation as (3.8) for a fixed quota model (FQ-system) is used for purposes of comparison with the EQ-system. The development here mainly follows Clark [4]. The regulator specifies here a total quota u_k for every period k that we as above assume is always taken except that there will always be a minimum $\underline{s}$ of recruits left. That is, harvest H_k in an FQ-system is given by

$$H_k = H_k(x_k, u_k) = \max(0, \min(x_k - \underline{s}, u_k)) \tag{3.14}$$

If s_0 denotes initial escapement, the optimal present value function $V^*(s_0)$ at an infinite time horizon satisfies Bellman's equation

$$V^*(s_0) = \max_{u_1 \geq 0} E\{\pi_1 + \alpha V^*(s_1|s_0)\} = \max_{u_1 \geq 0} E\{\pi_1 + \alpha V^*(x_1 - H_1(x_1,u_1)|s_0)\}$$

$$= \max_{u_1 \geq 0}\left[E_{x_1}\left\{pH_1(x_1,u_1) - \bar{c}\ln\left(\frac{x_1}{x_1 - H_1(x_1,u_1)}\right)\right\}\right. \tag{3.15}$$

$$\left. + \alpha E_{z_1}\{V^*(z_1G(r_0) - H_1(z_1G(s_0), u_1))\}\right]$$

The probability distribution function for x_2 in this case (and here is c not involved) is also given by equation (3.10), but here we have

$$z_2(x_1,x_2) = \frac{x_2}{G(x_1 - H_1(x_1,u_1))} \tag{3.16}$$

The optimal expected escapement for FQs is given by

$$E\left\{s_1^*\middle|s_0\right\} = E_{z_1}\left\{\max\left(\underline{s}, z_1 G(s_0) - H_1\left(z_1 G(s_0), u_1\right)\right)\right\} \tag{3.17}$$

In the following numerical examples two types of the stock-recruitment relationship $G(s)$ is specified. In example 1 and 2 the model is $G(s) = 1 - \exp(-2s)$ which without harvest has a stable equilibrium point 0.7968 while $G(s) = (1 - \exp(-2s))(1 - \exp(-10s))$ is a depreciation model with the natural stable equilibrium point 0.7963 and a unstable equilibrium point 0.07761 used in example 3 and 4. One calculation made for these examples is the probability for extinction after harvesting. For the model with depreciation, it is obvious that if next period recruitment x_2 is below the unstable equilibrium point, the population will eventually die out. The probability for extinction is therefore calculated as

$$\Pr\left(x_2 \le \underline{x}_2\right) = F_{x_2}\left(\underline{x}_2\right) = 1 - \int_{\underline{x}_2}^{\infty} f_{x_2}\left(x_2\right)dx_2 \tag{3.18}$$

where $\underline{x}_2$ = 0.07761 is the unstable equilibrium point of the model. Actually with the model used in example 1 and 2 where we assume a lower limit $\underline{s}$ for survivors there is no possibility for extinction. Here the same formula (3.18) and the same $\underline{x}_2$ value are used to calculate what one might call a pseudo probability for extinction.

For all examples the probability distribution functions for z and c are both assumed to be lognormal with a coefficient of variance of $\sigma_z = 0.5$ and $\left(\bar{c}\,\sigma_c\right)$ respectively. Price for fish is $p = 1$, the mean of unit effort cost is $\bar{c} = 0.1$ with relative coefficient of variance $\sigma_c = 1.0$ and the discount factor is $\alpha = 0.9$. For numerical convenience a confidence interval is specified for the distributions for z and c, so that these variables will have lower and upper limits ($z_{\min}, z_{\max}, c_{\min}, c_{\max}$) given by their respective $\frac{\beta}{2}$ - and $\left(1 - \frac{\beta}{2}\right)$ - quartiles where $\beta = 10^{-8}$. Due to the marginal cost function (2.6) we use, we want to denote the lower limit $\underline{s}$ as the *zero-profit level* of the stock. Then $\underline{s}$ is the solution of

$$p - \frac{c_{\min}}{\underline{s}} = 0 \text{ which gives } \underline{s} = \frac{c_{\min}}{p} = 6.0 \cdot 10^{-4} \tag{3.19}$$

Figures a) in the examples display the main result of the dynamic programming calculations. The optimal expected value of the fishery as a function of expected recruitment when the EQ system is used is compared to the deterministic result that gives a constant escapement policy and to the optimal expected value for the FQ system. The gap of the expected value of the fishery between the deterministic case and the case when FQs are used to regulate the fishery is considerably reduced by the EQ system. In example 1 where the *zero* “exact catch budget” condition is used to determine the subsidy parameter a_1, the gap is reduced by approximately 1/3 and in example 2, when only penalty is used to regulate the fishery (no price subsidy, $a_1 = 0$), the gap is approximately bisectioned. In example 3 and 4, we see a similar improvement of the expected value of the fishery for the EQ system, but here the high risk for resource collapse makes a deterministic knowledge more valuable.

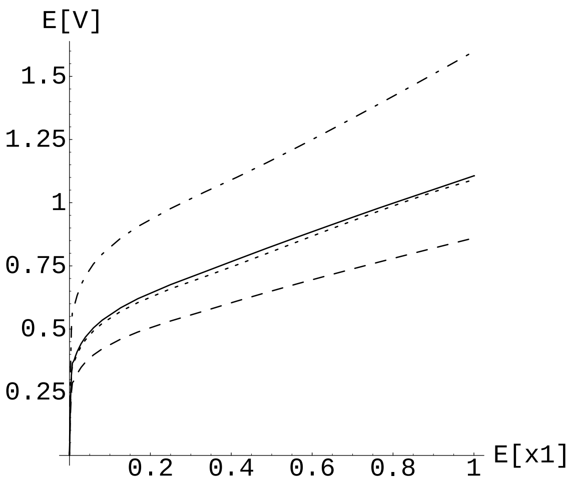
It is interesting to note the somewhat peculiar result of the EQ system that especially for example 3 and 4 optimal expected value is higher when the fishermen’s costs are uncertain compared to when the costs are known. The exception here is in figure 2b), when $a_1 = 0$, for large values of the expected recruitment where expected value when costs are uncertain is slightly lower. Normally one would expect lower optimal values with additional uncertainty, but this is not the case here. The reason for this might lie in the fact that the quadratic penalty function in use is not the optimal one and that “adding” cost uncertainty will initiate responses that are more alike the optimal response.

The figures b) in the panels show the corresponding optimal policy in the form of targets for expected escapement levels. Results from Clark [4] for FQs with various standard deviations indicate that the optimal threshold for when to start harvesting is lower the higher the uncertainty. The optimal harvest on the boundary when the threshold is exceeded will be low so that the harvest is safe in the sense that there will be no danger of extinction, and since uncertainty means the possibility of the stock becoming larger than the optimal deterministic threshold, it is optimal with a lower threshold than the deterministic. Notice here in the figures 1b) and 2b) the order of the thresholds that indicate the varied total uncertainty content. EQs with uncertain costs hold the highest total uncertainty in this context, FQs have lower uncertainty, while EQs with known costs hold the lowest except of course for the deterministic case. However, as the results here imply, when comparing EQs with uncertain costs and FQs, this is only the truth on the boundary when $E\{H_1\} \rightarrow 0$. In view of this it is also revealed that EQs with known costs on the boundary will have a lower total uncertainty content than corresponding FQs. This is probably also true for EQs when the cost uncertainty level is small.

Figure 1c) and 3c) shows the expected budget plotted as a function of expected recruitment while in figure 2c) and 4c) the ordinate is the expected budget minus the “exact catch budget” which must be withdrawn to make those figures comparable.

The figures d) in the panels show the probability for extinction on a logarithmic scale as a function of expected recruitment when the respective optimal policy is employed. Also shown are for the EQ-system the lower curves with the probability for extinction when expected harvest is equal to optimal expected harvest for FQs. The comparison in this case shows that the EQ-system with uncertain costs approximately halves the probability for extinction while when there are no uncertainty in the costs a further drop of the probability is seen especially when there are no price subsidy. These relations between the systems probably hold for any choice of the expected harvest for the fishery. With an EQ system at hand it is shown by the upper curves in figures d) that for a risk neutral regulator it is optimal to go for a harvest with higher risk of resource collapse than when he has a FQ instrument. An amount that is not calculated here is the target expected harvest for the EQ system that gives the same extinction risk as the FQ. The value of this extra harvest would be a direct measure of the Pareto improvement (free lunch) of a switch over from a FQ to an EQ system.

Panel for numerical example 1: "Exact catch budget" is *zero*



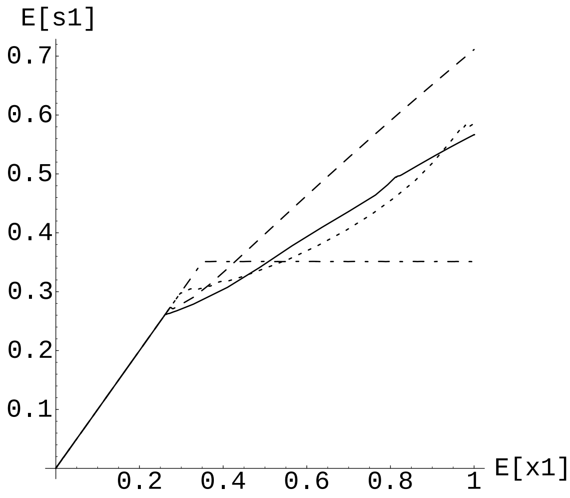
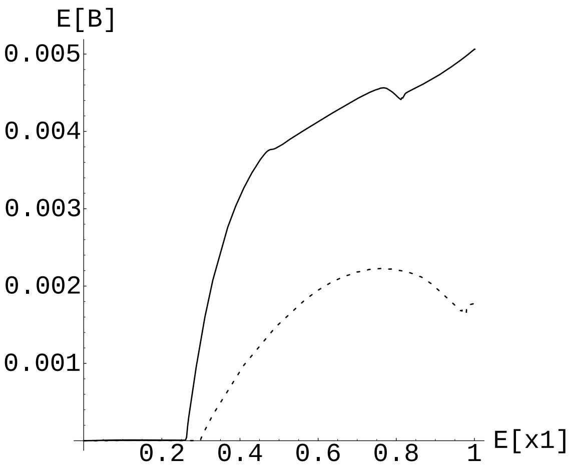


Figure 1a. Expected value vs expected recruitment.

Figure 1b. Expected escapement vs expected recruitment.

Deterministic	FQ	EQ with known costs	EQ with uncertain costs
- – - – - – -	– – – – – –	- - - - - - - - - - -	————————



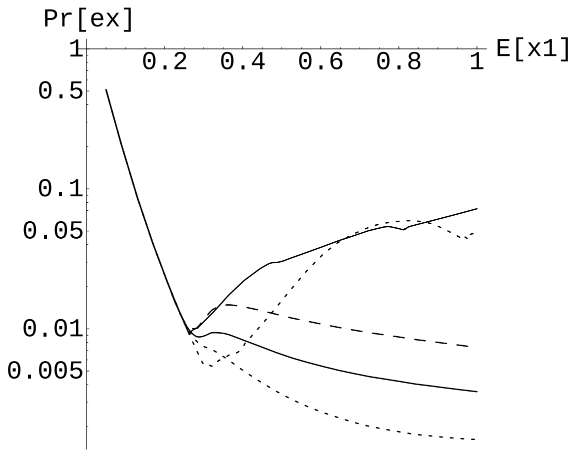


Figure 1c. Expected budget vs expected recruitment.

Figure 1d. Probability for extinction after harvesting.

Panel for numerical example 2: No price subsidy, only penalty in use

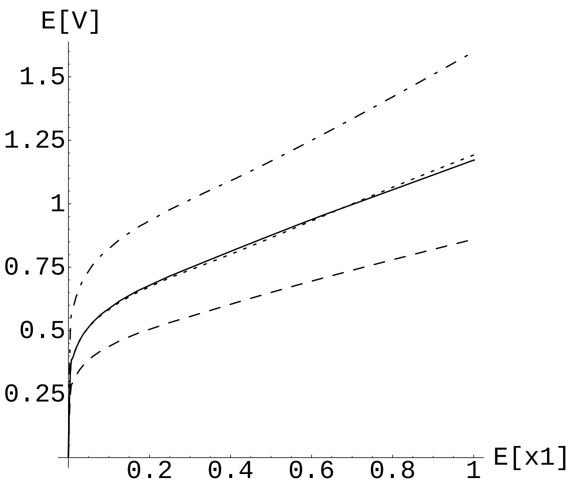


Figure 2a. Expected value vs expected recruitment.

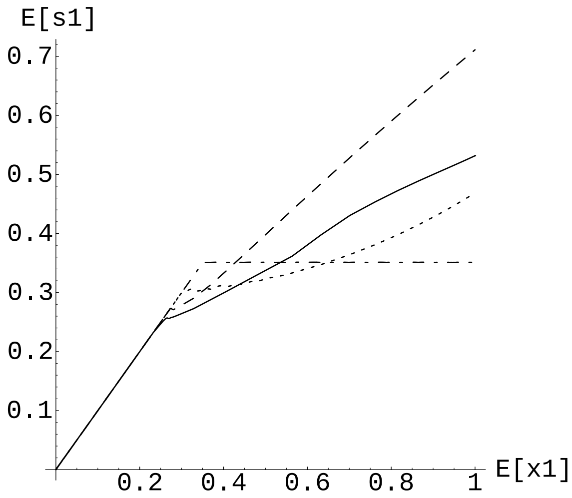


Figure 2b. Expected escapement vs expected recruitment.

Deterministic	FQ	EQ with known costs	EQ with uncertain costs
- — - — -	— — — — —	. . . .	————————

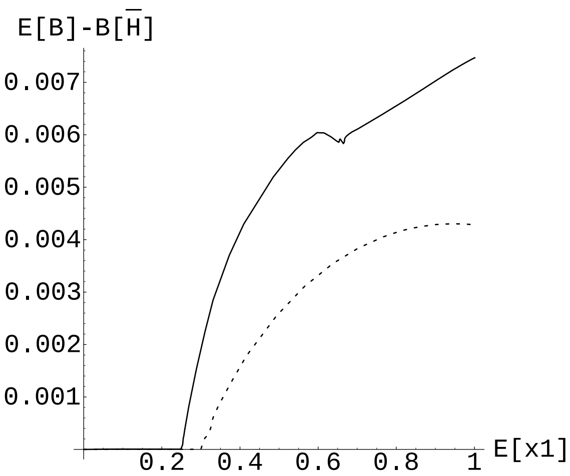


Figure 2c. Expected budget minus “exact catch budget” vs expected recruitment.

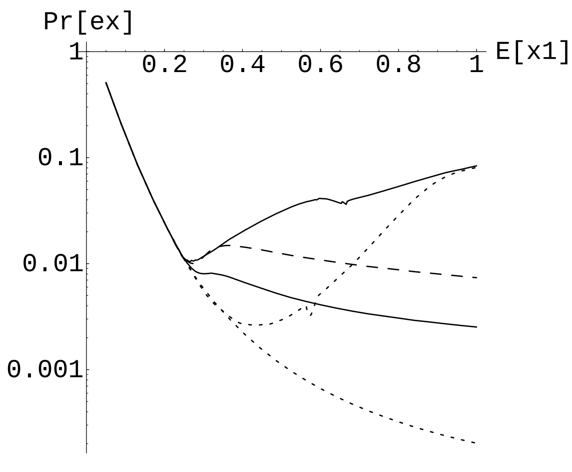


Figure 2d. Probability for extinction after harvesting.

Panel for numerical example 3: Depreciation model and "Exact catch budget" is *zero*

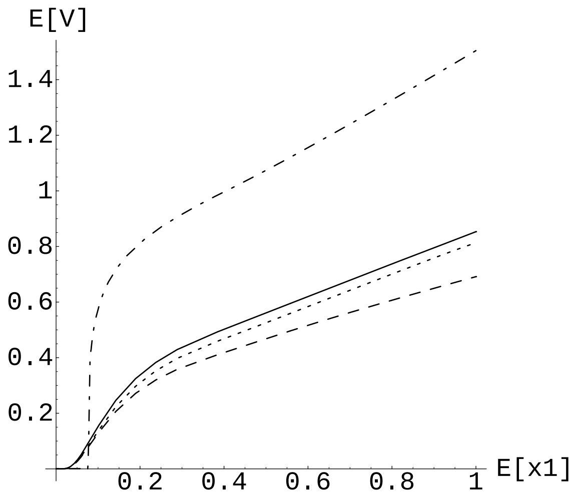


Figure 3a. Expected value vs expected recruitment.

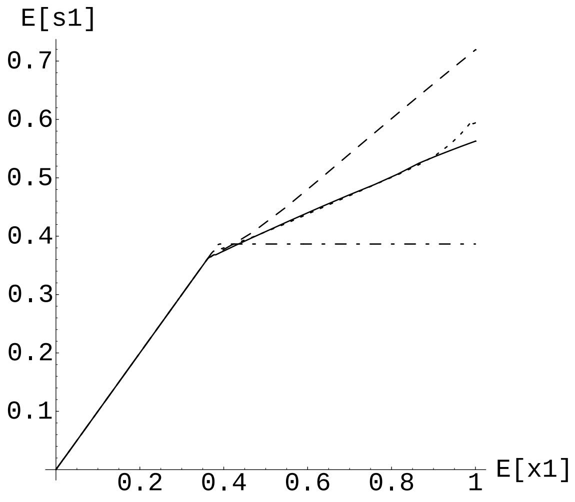


Figure 3b. Expected escapement vs expected recruitment.

Deterministic	FQ	EQ with known costs	EQ with uncertain costs
- — - — - —	— — — — — —	....	————————

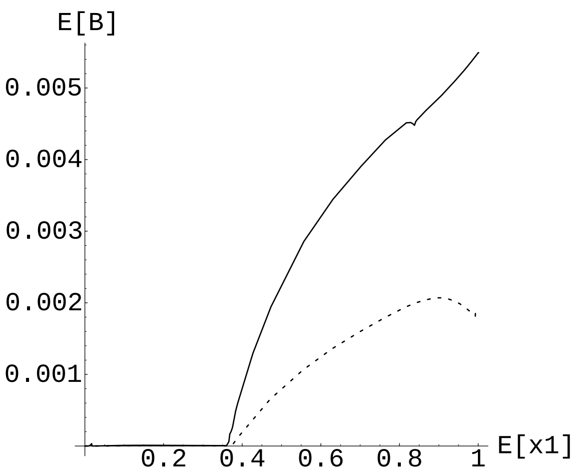


Figure 3c. Expected budget vs expected recruitment.

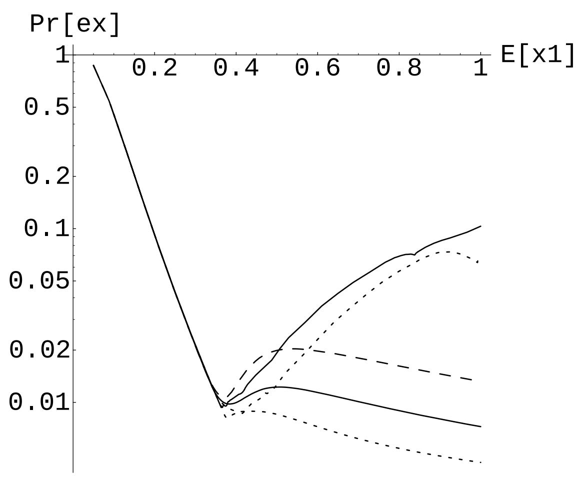


Figure 3d. Probability for extinction after harvesting.

Panel for numerical example 4: Depreciation model. No price subsidy, only penalty in use

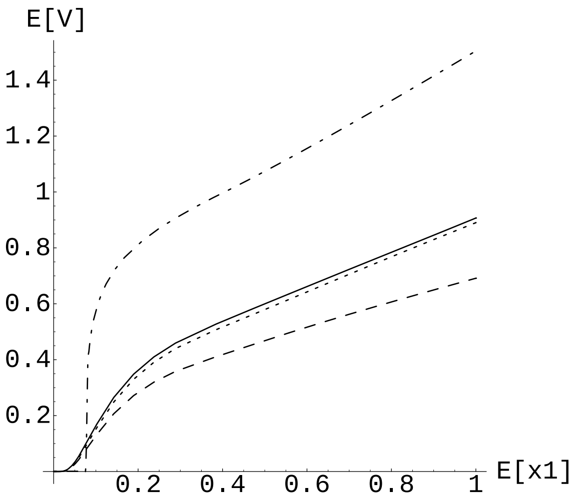


Figure 4a. Expected value vs expected recruitment.

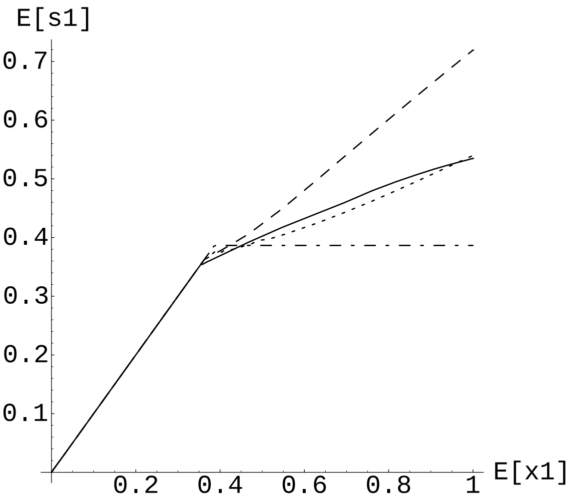


Figure 4b. Expected escapement vs expected recruitment.

Deterministic	FQ	EQ with known costs	EQ with uncertain costs
- — - — - —	— — — — — —	. . . .	————————

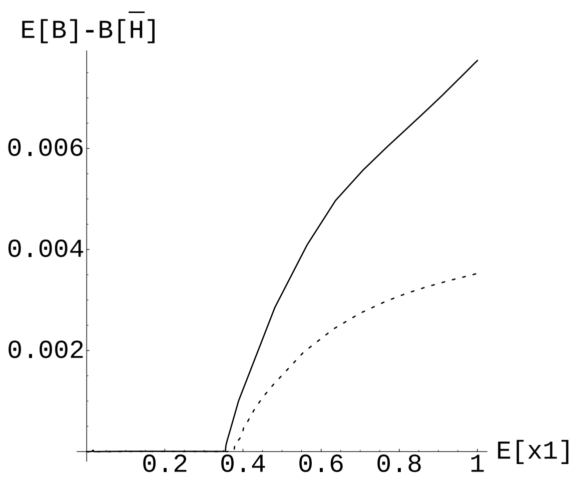


Figure 4c. Expected budget minus “exact catch budget” vs expected recruitment.

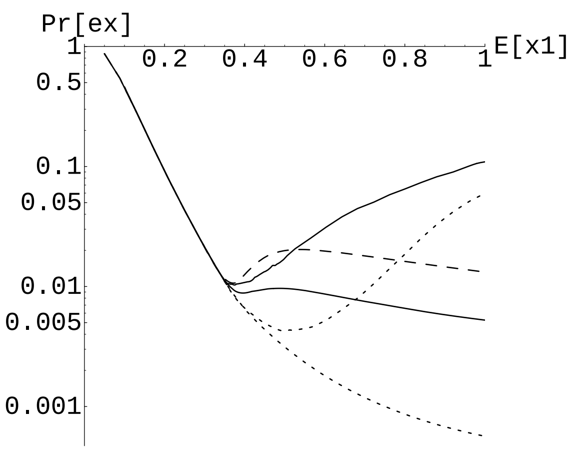


Figure 4d. Probability for extinction after harvesting.

4. INDIVIDUAL TRANSFERABLE EXPECTED QUOTAS

When EQs are tradable on a market, opportunity costs for not selling quotas will influence the profit function (2.5) that is maximized by the fishermen. Omitting the k index and denoting p as a constant market price for fish, the profit function for fisher i is

$$\gamma^i\left(H^i,d^i\right)=\left(p+a_1\right)H^i-\frac{a_2}{2d^i}\left(H^i\right)^2-C^i\left(\frac{H^i}{\bar{x}}\right)-m\,d^i\overline{H} \tag{4.1}$$

where m is the market price of an ITEQ unit[3] and $\overline{H}$ is the total allowable expected catch (TAEC) for the fishery. This function has a stationary point where $\gamma^i_{H^i}=0$ and $\gamma^i_{d^i}=0$ (subscripts denotes partial derivatives). For positive variables and parameters and an increasing cost function this point proves to be a maximum because $\gamma^i_{H^iH^i}\,\gamma^i_{d^id^i}-\left(\gamma^i_{H^id^i}\right)^2\geq 0$.

Assume that the fishers have a profit-maximizing behavior, except that they do not consider their influence on stock size, market price for fish and quota price. The equation retained from setting the partial derivative of (4.1) w.r.t. d^i to *zero* determines (omitting the negative solution) the following relationship between fisher i's demand for quota shares d^i and his choice of output H^i

$$d^i=H^i\sqrt{\frac{a_2}{2m\overline{H}}} \tag{4.2}$$

In equilibrium, when the quota market has "cleared", the total demand for quota shares is equal to the supply, and sum of all fishers output is equal to the realized total catch H. That is

$$1=\sum_i d^i=\sum_i H^i\sqrt{\frac{a_2}{2mH}}=H\sqrt{\frac{a_2}{2m\overline{H}}} \tag{4.3}$$

Assuming realized expectations $\overline{H}=H$, we find the following relationship between total catch H, quota price m and the a_2 regulation parameter

$$H=\frac{2m}{a_2} \tag{4.4}$$

Using this relationship, equation (4.2) becomes

$$d^i=\frac{a_2}{2m}H^i \tag{4.5}$$

The equation retained from setting the partial derivative of (4.1) w.r.t. H^i to *zero* determines fisher i's choice of output. When (4.5) is used, the equation becomes

$$C^i_{E^i}\left(E^i\right)=C^i_{H^i}\left(H^i\right)=\left(a_1+p-2m\right)\bar{x} \tag{4.6}$$

[3] This is acually the rental price of the quota unit. The real price is $\tilde{m}=m/(1-\alpha)$ where α is the discount rate.

In a “normal” ITQ system (with fixed quotas) the corresponding equation is (Clark [3])

$$C^i_{E^i}\left(E^i\right) = C^i_{H^i}\left(H^i\right) = \left(p - q\right)x \tag{4.7}$$

where q is the quota price in this system and where x can be interpreted as the mean stock size, $x = \bar{x}$. This equation compares those two quota prices:

$$m = \frac{a_1 + q}{2} \tag{4.8}$$

That is, if for example the a_1 subsidy parameter were set equal to *zero*, the EQ price m would be half of the price q of a FQ. The a_1 subsidy parameter, under the “exact catch budget” equal to *zero* condition, can be calculated when all expectations are fulfilled (the deterministic case). The budget w.r.t. fisher i is

$$\frac{a_2}{2d^i}\left(H^i\right)^2 - a_1 H^i \tag{4.9}$$

Substituting d^i in this equation with (4.5) and simplifying yields

$$\left(m - a_1\right)H^i \tag{4.10}$$

Since H^i is positive, the budget can only be *zero* if $a_1 = m$ and when this result is put into (4.8) one finds the following relationship

$$a_1 = m = q \tag{4.11}$$

That is, under the *zero* “exact catch budget” condition (and a deterministic model), the price subsidy parameter a_1 will be equal to the market price for a EQ share in a ITEQ system and these will also be equal to the price for a FQ share in the corresponding ITQ system.

5. SUMMARY AND PERSPECTIVE

The concept of individual expected quotas (EQs) must not be mistaken as just another alternative management system. It is more like a foundation stone that can be used to build management systems. As the idea of an individually fixed quota (FQ) is defined as a private property right, one has to grasp the idea of an individual expected quota as another type of private property right. Both concepts are management tools for centralized resource control, but while FQs in principle (or in their pure form) also centralize individual catch decisions, EQs principally decentralize them.

One of the reasons for the EQ system’s advantageous prospect in an “uncertain world” is its ability, at the point of time in the beginning of the regulation period, to “look into the future” and adapt total actual catch to the mean stock size of that period. Another reason is that it unties inefficient constraints that was introduced with FQs while at the same time it privatizes quotas enough so that it is unnecessary to race for the fish.

The choice of a quadratic penalty function might not be an optimal choice for a given dynamic structure of a fishery model, but it works well and is probably the best choice when it comes to practical usefulness. With this function, marginal revenue decreases linear with accumulated catch. The rule for the fisher is simply: Stop harvesting when marginal revenue is lower or equal to marginal costs.

To a certain degree, assuming that fishers' income today is binding, one can say that the choice of the subsidy parameter a_1 is free for the regulating authorities. Normally the fishing industry's is charged by the public taxation system through a linear tax on profit. If desirable one could charge all or a part of the same public tax as an amount proportional to revenue. That is in the EQ system to set a subsidy parameter that is lower than with the *zero* "exact catch budget"- condition. As proposed by the numerical results, this is advantageous.

In this paper the a_2 parameter is a constant which setting is determined by the chosen target expected escapement level. It might be prosperous however to substitute this parameter with a function linearly dependent on the individual mean price a fisherman gets for the fish he delivers through the regulation period; a boot-strapping function. The effect of this function is a reduction or if the dependency of this mean price over the function value is high enough a complete removal of the economic incentive for fishers to discard fish at sea. Taking the uncertainty of the amount of discarding that would occur in a FQ managed fishery into account, a EQ management system with this bootstrap mechanism will probably be more accurate when it comes to achieve a particular target harvest for the fishery. With this, also the effect on the numerical results above if the fish price p where not assumed constant should be minimal.

Traditionally, harvesting rights (FQs) have been allocated to participants of the harvesting sector only. Matulich [5,6] argues for the need also to allocate processing rights to the processing sector to achieve an efficient solution, the so-called two-pie allocation of rights. For a management system built with the EQ concept a similar solution will probably be necessary to get rid of the assumption used here that fishers must not be in collaboration or vertically integrated to the processing industry.

A management system with the EQ concept can favorably be used for regulation of several types of stock. Vessels opting for diverse fishing will get several EQs, and there will be an EQ for bycatches. Penalty fees for exceeding quotas on one species will be compensated by rewards for going under quota on other types. When nearing the end of a regulation period, decisions on how much to fish of each species may be taken on the last trip.

The need to report falsely on time and place for catches will diminish, mainly because a management system based on EQs allows for extensions above quotas and because fishing will not be aborted. Whereas FQ based regulatory systems may impose pressure on the government to increase quotas, with this the authorities may pass the ball back by claiming that fishermen themselves may increase catches by diminishing costs.

A trust in the stability of the system's parameters during the regulatory period must be ensured and all changes made known in advance. Or else what will happen is equivalent to what happens if there is uncertainty whether an initially fixed quota will still be allowed later in the regulation period; it will cause fishermen to "race for the fish" at the beginning of the period.

The distribution of income for the fishermen through the regulation period should continue to stay as it is today since the penalty/reward scheme can only be determined at the end of the period. The settlement process may be integrated to the system where advance tax deduction minus the income tax you are supposed to pay is debited or credited in arrears.

At each landing site it will be necessary with a computer that is part of an integrated network where all catches are registered. Since relatively cheap modern information technology is being used and most procedures can be made automatic, expenses for administration of such a regime will probably not exceed the costs of an ITQ-system. Expenses for monitoring and enforcement might be lesser. During an initial switchover period, costs may be more excessive at first.

To get such a regulatory regime going, one has to pass through a learning phase for both scientists, managers and fishers. Since there is no knowledge on how fishers will react to decreasing marginal revenue, the first empirical data should be generated "off-line" as computer games that combines experimental methods with game-theoretic models. Actual behaviour in diverse fisheries management regimes will then be comparable between them and to the theoretical benchmarks derived. A base line scenario has been developed for this purpose and a first pilot experiment has been run (Ostmann [7]).

APPENDIX A

THE CONTINUOUS TRANSFERABLE EXPECTED QUOTA SYSTEM

The symbols used are

t	Running time
r	Discount rate
$\bar{h}, \bar{h}^i$	Respectively total expected rate of catch and fisherman *i*'s allotted share of it
$x, \dot{x}$	Respectively stock size and it's time derivative.
$g(x)$	Natural growth function (continuous)
$e^i(\bar{h}^i, x)$	Fisherman *i*'s fishing effort rate
$h^i(e^i, x)$	Fisherman *i*'s harvesting rate function
$C^i(e^i)$	Fisherman *i*'s harvesting cost function
$T(h^i, \bar{h}^i)$	Penalty/reward function faced by fisherman *i*

The regulator's optimization problem is

$$\max_{\bar{h}, \forall \bar{h}^i \forall e^i} \sum_i \int_0^\infty \left[ph^i(e^i, x) - C^i(e^i)\right]\exp(-rt)dt \quad \text{where} \quad e^i = e^i(\bar{h}^i, x)$$

subject to
$$\dot{x} = g(x) - \sum_i h^i(e^i, x) \tag{A.1}$$
$$\sum_i \bar{h}^i = \bar{h}$$
$$x, e^i, \bar{h}^i \geq 0, \forall i$$

The current value Hamiltonian for the problem is

$$\mathbf{H} = \sum_i ph^i(e^i, x) - C^i(e^i) + \mu\left(g(x) - \sum_i h^i(e^i, x)\right) \tag{A.2}$$

Necessary conditions are

$$\mathbf{H}_{e^i} = \left((p-\mu)h^i_{e^i} - C^i_{e^i}\right) = 0, \quad \forall i \tag{A.3}$$

$$\mathbf{H}_{\bar{h}^i} = \left((p-\mu)h^i_{e^i} - C^i_{e^i}\right)e^i_{\bar{h}^i} = 0, \quad \forall i \tag{A.4}$$

$$\dot{\mu} - r\mu = -\mathbf{H}_x = \mu\left(\sum_i \left(h^i_x + h^i_{e^i}e^i_x\right) - g_x\right) - \sum_i \left(p\left(h^i_x + h^i_{e^i}e^i_x\right) - C^i_{e^i}e^i_x\right) \tag{A.5}$$

Fisher *i*'s optimization problem when he is compensated for changes in $\bar{h}$ is

$$\max_{e^i, \bar{h}^i} \int_0^\infty \left[ph^i(e^i, x) - T\left(h^i(e^i, x), \bar{h}^i\right) - C^i(e^i) - m\bar{h}^i\right]\exp(-rt)dt \quad \text{where} \quad e^i = e^i(\bar{h}^i, x).$$

subject to
$$\dot{x} = g(x) - \sum_i h^i(e^i, x) \tag{A.6}$$
$$e^i, \bar{h}^i \geq 0$$

The current value Hamiltonian for the problem is

$$\mathbf{H} = ph^i\left(e^i, x\right) - T\left(h^i\left(e^i, x\right), \bar{h}^i\right) - C^i\left(e^i\right) - m\bar{h}^i + \sigma^i\left(g(x) - \sum_i h^i\left(e^i, x\right)\right) \tag{A.7}$$

Necessary conditions are

$$\mathbf{H}_{e^i} = \left(\left(p - \sigma^i - T_{h^i}\right)h^i_{e^i} - C^i_{e^i}\right) = 0 \tag{A.8}$$

$$\mathbf{H}_{\bar{h}^i} = \left(\left(p - \sigma^i - T_{h^i}\right)h^i_{e^i} - C^i_{e^i}\right)e^i_{\bar{h}^i} - T_{\bar{h}^i} - m = 0 \tag{A.9}$$

$$\dot{\sigma}^i - r\sigma^i = -\mathbf{H}_x = \sigma^i\left(\sum_i\left(h^i_x + h^i_{e^i}e^i_x\right) - g_x\right) - \left(p - T_{h^i}\right)\left(h^i_x + h^i_{e^i}e^i_x\right) + C^i_{e^i}e^i_x \tag{A.10}$$

If the social shadow value μ of the resource (A.5) and shadow value $\sigma^i + T_{h^i}$ experienced by the fisher are equal, fisher *i* will follow the optimal harvesting path and the penalty/reward function found by combining (A.8), (A.9) and (A.10) is optimal. We see that this function will appear as a non-linear Pigouvian tax $T^*_{h^i}$ which is individualized by the transferable quota system.

If we assume that the fisher ignores the influence his catch has on the resource stock ($\sigma^i = 0$), it is possible to calculate a second best optimal penalty/reward function $T^{**}_{h^i}$ determined by aggregated measures of the fishery. Its time path is determined by (A.5) ($T^{**}_{h^i} = \mu$) and in bionomic equilibrium, $\dot{x}(t) = \dot{e}^i(t) = 0, \forall i$, $T^{**}_{h^i}$ is given by the equation

$$T^{**}_{h^i} = \frac{\sum_i\left(p\left(h^i_x + h^i_{e^i}e^i_x\right) - C^i_{e^i}e^i_x\right)}{\sum_i\left(h^i_x + h^i_{e^i}e^i_x\right) + r - g_x} \tag{A.11}$$

<u>The profit maximization problem for fisher *i* when he is not compensated</u> for changes in $\bar{h}$ is

$$\max_{e^i, z^i}\int_0^\infty\left[ph^i\left(e^i, x\right) - T\left(h^i\left(e^i, x\right), \bar{h}^i\right) - C^i\left(e^i\right) - mz^i\right]\exp(-rt)dt \quad \text{where} \quad e^i = e^i\left(\bar{h}^i, x\right).$$

subject to
$$\dot{x} = g(x) - \sum_i h^i\left(e^i, x\right) \tag{A.12}$$
$$\dot{\bar{h}}^i = z^i$$

The control variable z^i appears linearly in the problem so the optimal control will be of a bang-bang character. Since z^i is unbounded, expected quotas $\bar{h}^i$ will be instantaneously adjusted to desired levels.

The current value Hamiltonian for this problem is

$$\mathbf{H} = ph^i\left(e^i, x\right) - T\left(h^i\left(e^i, x\right), \bar{h}^i\right) - C^i\left(e^i\right) - mz^i + \rho^i z^i + \sigma^i\left(g(x) - \sum_i h^i\left(e^i, x\right)\right) \tag{A.13}$$

The necessary conditions are

$$m = \rho^i \text{ if the fisher is active, or } m \geq \rho^i \text{ if he is not active} \tag{A.14}$$

$$\mathbf{H}_{e^i} = \left(\left(p - \sigma^i - T_{h^i}\right)h^i_{e^i} - C^i_{e^i}\right) = 0 \tag{A.15}$$

$$\dot{\rho}^i - r\rho^i = -\mathbf{H}_{\bar{h}^i} = -\left(\left(\left(p - \sigma^i - T_{h^i}\right)h^i_{e^i} - C^i_{e^i}\right)e^i_{\bar{h}^i} - T_{\bar{h}^i}\right) \tag{A.16}$$

$$\dot{\sigma}^i - r\sigma^i = -\mathbf{H}_x = \sigma^i\left(\sum_i\left(h^i_x + h^i_{e^i}e^i_x\right) - g_x\right) - \left(p - T_{h^i}\right)\left(h^i_x + h^i_{e^i}e^i_x\right) + C^i_{e^i}e^i_x \tag{A.17}$$

If $\sigma^i = 0$, and if actual quota rate is equal to the expected one ($T_{h^i}h^i_{e^i}e^i_{\bar{h}^i} = -T_{\bar{h}^i}$), combining (A.14) and (A.16) and further follow the argumentation performed by Arnason [1], an optimal T function yields an equation that declare the motion of the equilibrium quota price of the following form

$$\dot{m} - rm = -\left(ph^i_{e^i} - C^i_{e^i}\right)e^i_{\bar{h}^i} \tag{A.18}$$

This means that the Minimum Information Management program can be used to set the total expected quota rate.

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LIST OF SYMBOLS

i	Fisherman index number. When index is missing: aggregated variables.
k	Year index. When index is missing: $k = 1$
$a_{1,k}$	Subsidy parameter, year k
$a_{2,k}$	Penalty parameter, year k
d_k^i	Fisherman i's allotted share of total expected catch; expected quota in year k
E_k^i	Fisherman i's actual accumulated effort in year k
H_k^i	Fisherman i's actual accumulated harvest in year k
$\hat{H}_k^i$	Fisherman i's planned accumulated harvest in year k
$\overline{H}_k$	Total allowable expected catch in year k
p	First-hand price for fish (assumed constant)
γ_k^i	Fisherman i's actual profit in year k
$\hat{\gamma}_k^i$	Fisherman i's planned profit in year k
π_k	Sosial economic revenue in year k
$C^i(\cdot)$	Fisherman i's cost function (assumed identical for any year)
e_k^i	Fisherman i's intermittant effort rate in the beginning of year k
e^i	Fisherman i's effort rate
h^i	Fisherman i's harvest rate
x	Current stock size
x_k	Intermittant stock size in the beginning of year k
$\overline{x}_k$	Mean stock size over year k
c	Cost of unit effort.
$\overline{c}$	Mean cost of unit effort.
$\underline{s}$	Part of stock that always escapes from harvesting
z_k	Stochastic variable in stock-recruitment relationship in year k
$\overline{z}$	Mean of stochastic variable in stock-recruitment relationship
$G(\cdot)$	Stock-recruitment relationship function
s_k	Escapement at end of year k
$f_v(v)$	Probability density function for variable v
$E\{\cdot\}$	Expectation operator w.r.t. all variables in expression
$E_v\{.\}$	Expectation operator w.r.t. variable v
α	Discount factor
$V^*(s_k)$	Optimal present value function for year k+1
$B_k(\overline{H}_k)$	Exact catch budget for year k
$\overline{B}_k$	Expected budget
σ_z, σ_c	Relative coefficient of variance for z and c respectively
$z_{\min}, z_{\max}$	Lower and upper limits for z in confidence intervall
$c_{\min}, c_{\max}$	Lower and upper limits for c in confidence intervall
β	Parameter determining quartiles for two-sided confidence interval
m	Quota price for expected quota system
q	Quota price for fixed quota system