The XI^th Annual Conference of the European Association of Fisheries Economists

Dublin 6th - 10th April 1999

Rethinking Property Rights - Introducing Flexible Quotas for Fisheries Management under Uncertainty

Helge Berglann

University of Oslo

Helge Berglann
Bio/Zoo, University of Oslo
P. Box 1050, Blindern
0316 OSLO
NORWAY
E-mail: berglann@bio.uio.no

Phone: 047 22 85 57 35 Fax: 047 22 85 46 05

Abstract

This paper proposes a new management tool called flexible quotas. The individual fisherman is faced with a scheme that imposes a penalty or grants a reward dependent on whether he chooses to exceed or go under the allocated quota. By making the penalty higher than the reward for the same deviation, the effect is an increase in the marginal cost for the fishers. This brings forth a regime where the sum of fishermen's actual catches will adapt to the mean stock size over the regulation period. Actual harvest will be lower than expected when the stock level is overestimated and vice versa. Compared to regimes where total quotas are determined at the start of the period, flexible quotas effectively reduce uncertainties about future recruitment, reduce the risk of resource collapse and moderate natural fluctuations. Problems such as high-grading and misreporting might be severe with individually fixed quotas, but can be almost eliminated here by introducing a bootstrapping mechanism. By resembling the Individual Transferable Quota (ITQ) system for fixed quotas, efficient distribution of flexible quotas is secured.

Calculations by means of dynamic programming give in a numerical example the result that the gap in economic value of the fisheries, when there are no uncertainties involved and when there are fixed quotas and uncertainty in the stock abundance estimate, is reduced with about 1/3. If only penalty were used to regulate fisheries, the same gap would be bisectioned. Uncertainties in fishermen’s costs have a marginal positive effect on these results.

Keywords:

Total Allowable Flexible Catch (TAFC), Individual Flexible Quota (FQ), Individual Transferable Flexible Quota (ITFQ).

1. Introduction

Total Allowable Catch (TAC) is a concept that has been in use ever since the early history of fisheries management. It fixes an upper limit for exploitation of a species in a resource pool 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 activities by administrative decrees, e.g. limiting days at sea, closed areas, closed seasons and so on. 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 quotas in fisheries are considered a more efficient way to implement regulation because the "race" will vanish when each individual fisher has only his own share of the fishing to worry about. In the following these individually fixed quotas will be referred to as “Normal Quotas” (NQs).

This article presents the idea that the use of the TAC-concept and the NQ-concept can be favorably replaced by what I respectively call a Total Allowable Flexible Catch (TAFC) and an individually Flexible Quota (FQ). As the NQ is a private property right under a TAC umbrella, the FQ corresponds to a private property right under the TAFC umbrella. Section 2 explains the basics of the FQ-system and argues why management problems are better handled here. By means of dynamic programming, section 3 compares the NQ and FQ systems in cases where there is uncertainty in stock assessment and fishermen’s costs.

Section 4 compares the systems w.r.t. the economic incentive for high-grading. It shows how a simple bootstrap mechanism built into the FQ system can reduce or almost eliminate the economic incentive for this “bad” fisherman behavior that comes with the use of NQs.

Section 5 solves the problem that arises due to the amount of information required for an efficient distribution of quotas in an FQ-system. FQs resemble NQs in many respects. Thankfully, many of the ideas in fishery economic literature on how to enhance quota management qualities for NQs will still be useful for FQs. Bringing the idea of the well known Individual Transferable Quota (ITQ) system into the world of FQs, the result becomes what can be called the Individual Transferable Flexible Quota (ITFQ) system.

2. The Pure Individual Flexible Quota (FQ) System

The basis for the pure FQ system I propose is that first the regulator (Fisheries Authorities) rename the concept of Total Allowable Catch (TAC) and call it Total Allowable Flexible Catch (TAFC). Then he allocates shares of what is now called the TAFC to each fisherman and call it FQs. This allocation of FQs implies that each fisherman must sign a contract, which allows him to exceed the allocated quota. If he does, he will however be obligated to pay a penalty. On the other hand, if he catches less then the quota, he will receive a reward.

The main ingredient of the FQ concept is that the penalty for going over the quota with a certain quantity is higher than the reward for going under with the same quantity. The effect of this penalty/reward rule is to rise the marginal cost for the fisherman with the catch he accumulates through the year. Due to this, the fisherman will face a limitation in his catch because sooner or later the vessel will gather a catch that is unprofitable to exceed. The formal definition of a Flexible Quota (FQ) is (from the regulators view) the expected catch for the vessel allocated this quota, and the formal definition of Total Allowable Flexible Catch (TAFC) is the expected total catch of the fishery. If the regulator possessed full information on the fishery, the expected catch could be realized, but since he obviously has limited information actual catch will deviate from the expected. This is the conceptual content of the term "flexibility" that gives this system its name.

The advantageous prospect with this is that for a fisherman who schedules his catch through the year properly, the point of time when he decides to stop fishing will be at the end of the regulation period. His actual catch will thereby be influenced by the current stock size at that point in time because 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-NQ 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, reduce the risk of resource collapse and give a higher expected recruitment after harvest than the NQ system. 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].

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

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

emerge if all fishemen were to fill their FQs 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. 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[2].

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. A lump sum tax would probably not be advisable because normally it is optimal to keep the price subsidy as low as possible.

During my investigation I have found it difficult to synthesize the form of the penalty/reward scheme that would be optimal. For sake of simplicity (not at least for the fishermen), I choose a quadratic FQ-system. Here the regulator imposes fisherman *i* in year *k* a price subsidy $a_{1,k} H_k^i$ and a quadratic penalty chosen to be of the form $\bar{p}_k^i \frac{a_{2,k}}{2 d_k^i} \left(H_k^i \right)^2$ where $\bar{p}_k^i$ is the mean price for the fish he delivers through the year[3], 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. Also assume that $\bar{p}_k^i$ is constant in the sense that it is independent of total harvest H_k. 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

[2] Figure 1d in section 3 displays a numerical example of the expected budget as a function of expected recruitment.
[3] This price is supposed to be individual and weighted with the deliveries over the year.

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 fisherman *i* is maximizing is given by

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

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

$$\text{(2.2)} \quad h^i = x\,e^i$$

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

$$\text{(2.3)} \quad H_k^i = \overline{x}_k E_k^i$$

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

$$\text{(2.4)} \quad \overline{x}_k = \frac{x_k + x_{k+1}}{2}$$

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

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

Assuming a perfect distribution of FQs, 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

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

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

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

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

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

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

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

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

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

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

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

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

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

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 H_k (TAFC) 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 Flexible Catch

This section's aim is to determine the optimal parameters of the FQ system and to compare the result with the optimal solution for NQs. 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, 1979) is given by:

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

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 to be 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

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

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

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

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 Flexible Catch (TAFC)</u> and is given by

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

As noted in the above section, we assume the price subsidy parameter $a_{1,k}$ when $a_{2,k}$ and s_{k-1} is 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

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

where $\bar{p}_k$ is the mean price of fish over year *k*, assumed to be independent of $\overline{H}_k$. The solution of $a_{1,k}$ is then found through the implicit equation $B_k(\overline{H}_k) = 0$. 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

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

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

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

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

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

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

(3.8) $$= \max_{a_{2,1}}\left[E_c E_{x_1} E_{z_2}\left\{\bar{p}_1 H_1\left(z_2, x_1, c, a_{2,1}\right) - c\ln\left(\frac{x_1}{x_1 - H_1\left(z_2, x_1, c, a_{2,1}\right)}\right)\right\}\right.$$

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

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, $f_{x_1}(x_1)$, is needed for calculation of (3.8). It is given by

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

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

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

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

$$(3.11) \quad f_{x_2}(x_2) = \int_0^\infty f_{x_2|c}(x_2, c) f_c(c) dc \text{ where } f_{x_1|c}(x_2, c) = f_{x_2}(x_2) \text{ in (3.10)}$$

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

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

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

$$(3.13) \quad \overline{B}_1 = E\{B_1|s_0\} = E_c E_{z_1} E_{z_2} \{\overline{p}_1 a_{2,1} H_1^2(z_2, z_1 G(s_0), c, a_{2,1}) - a_{1,1}(a_{2,1}) H_1(z_2, z_1 G(s_0), c, a_{2,1})\}$$

A similar Dynamic Programming equation as (3.8) for a fixed quota model (NQ-system) is used for purposes of comparison with the FQ-system. The development here mainly follows Clark, 1986. 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 $\breve{s}$ of recruits left. That is, harvest H_k in a NQ-system is given by

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

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

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

(3.15) $$= \max_{u_1 \geq 0}\left[E_{x_1}\left\{\bar{p}_1 H_1(x_1, u_1) - \bar{c}\ln\left(\frac{x_1}{x_1 - H_1(x_1, u_1)}\right)\right\}\right.$$

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

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

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

The optimal expected escapement for NQs is given by

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

In the following examples the stock-recruitment relationship is specified to $G(s) = 1 - \exp(-2s)$ and 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 $(\bar{c}\ \sigma_c)$ respectively. Price for fish is $\bar{p}_1 = 1$, 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 $\breve{s}$ as the *zero-profit level* of the stock. Then $\breve{s}$ is the solution of

(3.18) $\bar{p}_1 - \frac{c_{\min}}{\breve{s}} = 0$ which gives $\breve{s} = \frac{c_{\min}}{\bar{p}_1}$

Figures a) in the examples display the main results from the dynamic programming optimization and figures b) show the corresponding optimal policy in the form of targets for expected escapement levels, all as a function of expected recruitment. The optimal expected value of the fishery when the FQ system is used is compared to the deterministic result which gives a constant escapement policy and to the optimal expected value for the NQ system. The gap of the expected value of the fishery between the deterministic case and the case when NQs are used to regulate the fishery is considerably reduced by the FQ system. In example 1 where the condition “exact catch budget”=0 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 ($a_1 = 0$), the gap is approximately bisectioned.

It is interesting to note the somewhat peculiar result of the FQ system that optimal expected value is slightly 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, here the 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.

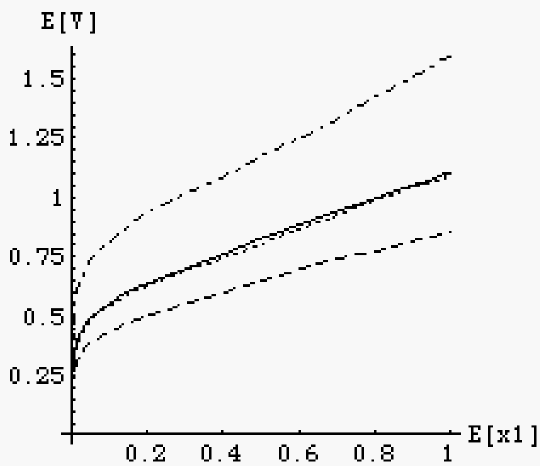
Figure 1c) shows the expected budget plotted as a function of expected recruitment while in figure 2c) the ordinate is the expected budget minus the “exact catch budget” which must be withdrawn to make those figures comparable. Both from the figures b) and even more distinctly in the figures c) one can notice different phases for the effect employed by the FQ system for various values of the expected recruitment.

Results from Clark, 1985, for NQs 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 b) the order of the thresholds which indicate the varied total uncertainty content. FQs with uncertain costs hold the highest total uncertainty in this context, NQs have lower uncertainty, while FQs with known costs hold the lowest except of course for the deterministic case. But as the results here imply, when comparing FQs with uncertain costs and NQs, this is only the truth on the boundary when $E\{H_1\} \to 0$. In view of this it is also revealed that FQs with known costs on the boundary will have a lower total uncertainty content than corresponding NQs. This is probably also true for FQs when the cost uncertainty level is small.

Behind every choice of target value for the expected escapement for each value of the expected recruitment $E\{x_1\} = G(s_0)$ lies a corresponding probability distribution function (PDF) for x_2, the recruitment after harvesting. The figures d) in the examples, is an example of this. Simplified one could say that the PDFs will have different shapes dependant on whether the harvest is small, medium or large and that it is these changes of shapes that are responsible for the different modes one can see in the figures b) and c). With small values of $E\{H_1\}$ the resulting PDFs are dome shaped, much like the PDF for FQs with known costs in the figures d). For medium values of $E\{H_1\}$ the shape of the PDF changes and becomes like the PDF for FQ with uncertain costs in the figures d) where a small portion of the probability mass is collected at values near zero. For large values of $E\{H_1\}$ the shape of the PDF will have two peaks where a substantial portion of the probability mass is collected at values near zero. Looking thoroughly at the PDF for NQs in the figures d) one will, to a certain extent, find this type of shape here.

The figures d) need more comments. It is an arbitrary example where we assume that the regulator has estimated the stock size to $\overline{x}_1 = 0.6$ (which corresponds to a known escapement level $s_0 = 0.458$ from last year) and he chooses a target expected escapement level $E\{s_1\} = 0.375$ which corresponds to the expected harvest $E\{H_1\} = \overline{x}_1 - E\{s_1\} = 0.225$. By inspection one can see, and it is also calculated in table 1, that the PDFs for x_2 for the various systems differ both in expected recruitment E(x_2) and standard deviations SD(x_2). The percentage increase of E(x_2) and decrease of SD(x_2) relative to the values for NQs is also calculated.

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



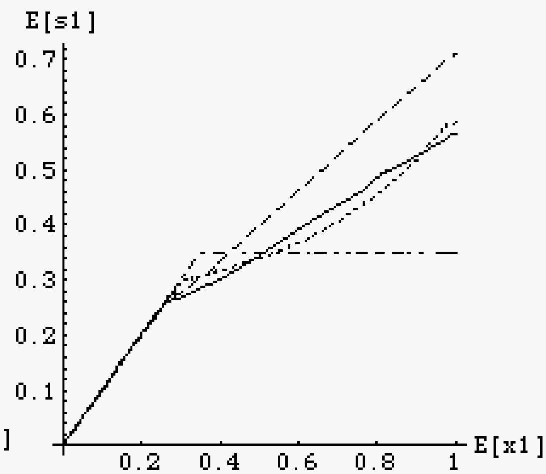
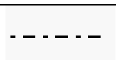
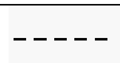
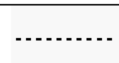
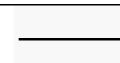
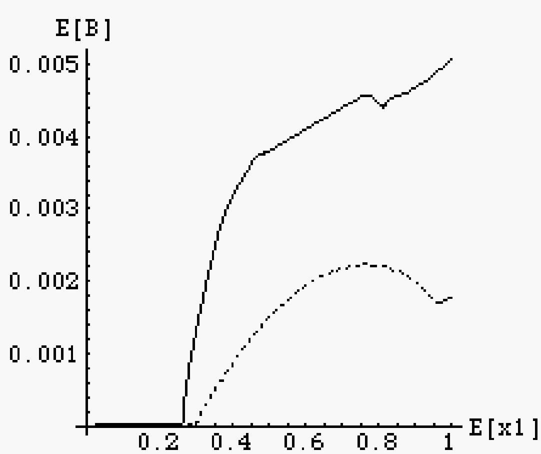


Figure 1a. Expected value vs expected recruitment. Figure 1b. Expected escapement vs expected recruitment.

Deterministic	NQ	FQ with known costs	FQ with uncertain costs
			



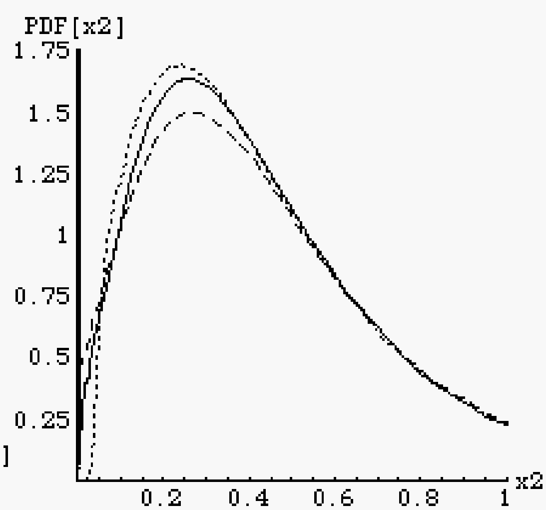
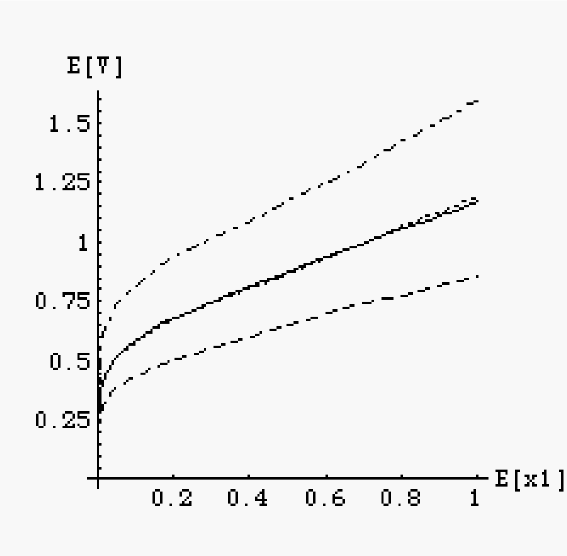


Figure 1c. Expected budget vs expected recruitment. Figure 1d. Probability density after harvesting.

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



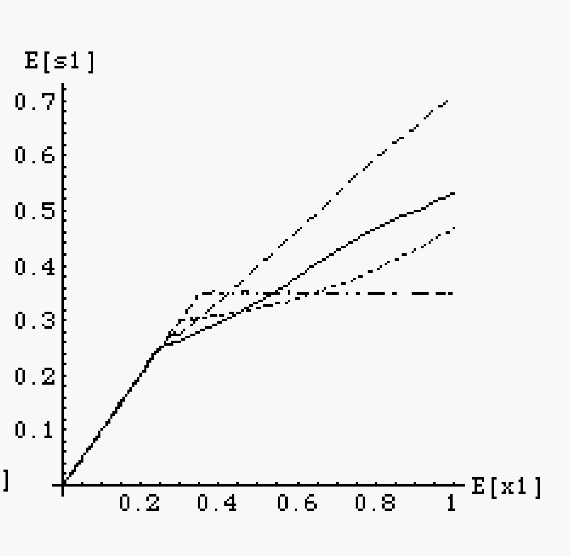
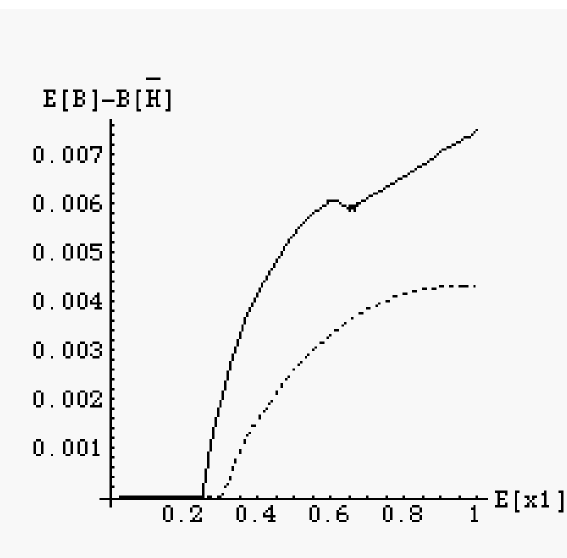


Figure 2a. Expected value vs expected recruitment. Figure 2b. Expected escapement vs expected recruitment.

Deterministic	NQ	FQ with known costs	FQ with uncertain costs
-·-·-	- - - - -	....	————



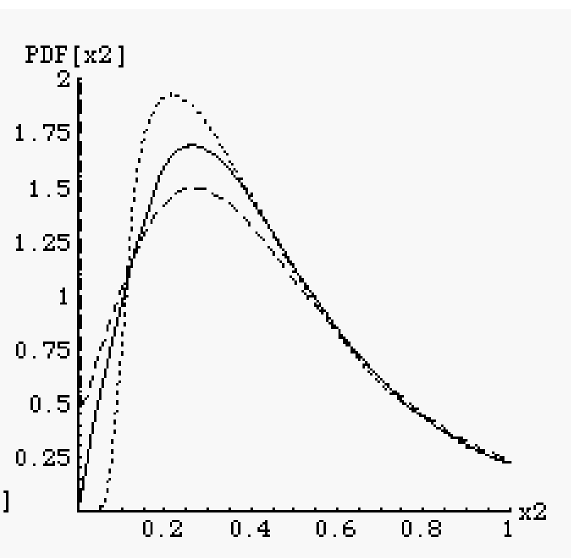


Figure 2c. Expected budget minus “exact catch budget” Figure 2d. Probability density after harvesting.

vs expected recruitment.

Since in this model we assume a lower limit $\breve{s}$ for survivors, actually there is no possibility for extinction. For comparison we want however to use a pseudo definition for extinction. Inspecting the probability distribution for NQs and the case for FQs with uncertain costs in figure 1b) thoroughly one sees that a part of the probability mass is near zero. This is also the case in figure 1b) for FQs with uncertain costs. The other pictures of the PDF for FQs will also have a probability mass near zero, but this is not shown here because of limitations of the numerical accuracy in the calculations. The pseudo definition for extinction is here calculated as

$$(3.19)\quad \Pr(x_2 \leq \breve{x}_2) = F_{x_2}(\breve{x}_2) = 1 - \int_{\breve{x}_2}^{\infty} f_{x_2}(x_2)dx_2$$

where $\breve{x}_2 = 0.05$ is a value chosen by visual inspection so that the probability mass near zero is discarded.

Table 1

Example in figure 1d and 2d: E(x_1)=0.6, E(H_1)=0.225	Control variables	Expected Recruitment after Harvesting E(x_2) % increase	Standard Deviation after Harvesting SD(x_2) % decrease	Probability for Extinction Pr($x_2 \leq \breve{x}_2$) % ratio
Normal Quota (NQ)	u_1=0.2262	0.45842	0.35279	0.0625
FQ, known costs	a_1=0.7470 a_2=6.6396	0.46290 0.9773 %	0.33440 5.2127 %	0.00506 8.096 %
FQ, uncertain costs	a_1=0.7581 a_2=6.7389	0.46124 0.6152 %	0.33907 3.8890 %	0.0320 51.20 %
FQ, known costs	a_1=0.0 a_2=3.3631	0.46565 1.5772 %	0.32060 9.1244 %	0.000135 0.216 %
FQ, uncertain costs	a_1=0.0 a_2=3.4395	0.46195 0.7700 %	0.33143 6.0546 %	0.0256 40.96 %

4. Incentives for high-grading

"Discarding of fish at sea is a problem of significant and increasing concern. To fishermen, the processing industry, and the marketing industry, these fish represent a loss of potential income, particularly when the mortality rate of discarded individuals is high. To managers and scientists monitoring the fishery, discards are an uncounted component of the catch, which results in underestimates of fishing mortality and, therefore, poor estimates of population size and productivity" (Gillis et al., 1995).

High-grading behavior is here defined as the discard of fish of low landing value in order to replace it with fish of higher landing value. It happens when fishers are faced with a constraint and when there is a price differential large enough to cover the cost of harvesting more fish to replace those thrown overboard.

Assume that skipper *i* uses the following rule for each fish on the deck: If the landing price p^i the fisher gets is lower or equal to a price p_b^i, throw it overboard. If the landing price p^i is higher than the price p_b^i, bring it on shore and sell it. The aim in this section is, by a static model, to compare the effects of the constraints employed by the FQ system and the NQ-system by investigating how bad the quality of the fish (measured by the landing price p_b^i) has to be before the economic incentive to throw it out appears. In case of high-grading behavior the profit function maximized by skipper *i* is

$$(4.1) \quad \gamma_d^i = \left(\overline{p}_g^i + a_1\right)H_g^i - \overline{p}_g^i \frac{a_2}{2d^i}\left(H_g^i\right)^2 - C\left(\frac{H_d^i}{\overline{x}}\right)$$

where H_g^i is skipper's chosen quantity of good valued fish, where $\overline{p}_g^i$ is the mean price for the good valued fish and where H_d^i is total harvest (including the part discarded) performed by the fisher to achieve H_g^i.

Assume that the vessel *i*'s catch composition (measured by the landing price p^i) is distributed with a probability density function $f_{p^i}^i\left(p^i\right)$ with mean price $\overline{p}^i$ and where $F_{p^i}^i\left(p^i\right)$ denotes the cumulative distribution function. The mean price of good valued fish $\overline{p}_g^i$ is then calculated as the mean of the lower truncated (at price p_b^i) distribution

$$(4.2) \quad \overline{p}_g^i\left(p_b^i\right) = \int_{p_b^i}^{\infty} p^i \frac{f_{p^i}^i\left(p^i\right)}{\left(1 - F_{p^i}^i\left(p_b^i\right)\right)} dp^i$$

and the total harvest H_d^i is given by

(4.3) $$H_d^i\left(p_b^i\right) = \frac{H_g^i}{\left(1 - F_{p^i}^i\left(p_b^i\right)\right)}$$

The profit function for fisher *i* in a NQ system is found from (4.1) by setting $a_2 = 0$ and $a_1 = 0$. The fisher maximizes the profit by choosing p_b^i and H_g^i subject to the quota constraint H^i. That is

(4.4) $$\max_{p_b^i, H_g^i \le H^i} \left\{ \gamma_d^i = \overline{p}_g^i\left(p_b^i\right) H_g^i - C^i\left(\frac{H_g^i\left(p_b^i\right)}{\overline{x}}\right) \right\}$$

Obviously the quota constraint is binding, that is $H_g^i = H^i$, and we can use the Lagrangean Multiplier Method to solve the problem. The Lagrangean function is

(4.5) $$L = L\left(H_g^i, p_b^i, \lambda\right) = \gamma_d^i\left(H_g^i, p_b^i\right) - \lambda\left(H_g^i - H^i\right)$$

where □ is the multiplier (or the shadow price). The following three equations is used to find the three unknowns □ , p_b^i and H_g^i

(4.6) $L_{H_g^i} = 0$, $L_{p_b^i} = 0$ and $H_g^i = H^i$

where subscripts denote partial derivatives.

For the FQ system, first the regulation parameters a_1 and a_2 has to be determined. When there is no high-grading (hold strategy), the profit function maximized by fisher *i* is

(4.7) $$\gamma_h^i = \left(\overline{p}^i + a_1\right) H_h^i - \overline{p}^i \frac{a_2}{2d^i}\left(H_h^i\right)^2 - C^i\left(\frac{H_h^i}{\overline{x}}\right)$$

where $\overline{p}^i$ is the mean price and H_h^i is the harvest chosen by the fisher. The budget restriction w.r.t. this fisher and a FQ equal to $H^i = d^i H$ where *H* is the TAFC, gives us in this static setting the following two equations to determine a_1 and a_2

$$\text{(4.8)} \quad \overline{p}^i \frac{a_2}{2}\left(H^i\right)^2 - a_1 H^i = 0 \quad \text{and} \quad \left.\frac{d\gamma_h^i}{dH_h^i}\right|_{H_h^i = H^i} = 0$$

For example, for a homogeneous fleet where all have the same linear marginal cost function (2.6), this determines a_1 and a_2 to be

$$\text{(4.9)} \quad a_1 = \overline{p}^i - \frac{c}{\overline{x}} \quad \text{and} \quad a_2 = \frac{2d^i\left(\overline{p}^i \overline{x} - c\right)}{\overline{p}^i \overline{x} H^i}$$

Next, we maximize (4.1) (with (4.2) and (4.3) inserted) with the control variables p_b^i and H_g^i. There is no constraints here, so the equations

$$\text{(4.10)} \quad \frac{d\gamma_d^i}{dH_g^i} = 0 \quad \text{and} \quad \frac{d\gamma_d^i}{dp_b^i} = 0$$

solved simultaneously w.r.t. p_b^i and H_g^i will give the answer. Note that here a choice $p_b^i > 0$ means a choice $H_g^i < H^i$.

The amount of discarded fish relative to what the fisher actually delivers on shore H_g^i with the choice p_b^i is calculated as (in percent)

$$\text{(4.11)} \quad D^i\left(p_b^i\right) = \frac{F_{p^i}^i\left(p_b^i\right) H_d^i}{H_g^i} 100\% = \frac{F_{p^i}^i\left(p_b^i\right)}{\left(1 - F_{p^i}^i\left(p_b^i\right)\right)} 100\%$$

<u>A numerical example</u>

Assume that the landing price p^i fisher *i* achieves have a lognormal distribution with mean price $\overline{p}^i = 1$ and standard deviation $\sigma_{p^i}^i = 0.4$. Further, assume that the cost is linear (2.6) with *c*=0.1, the mean stock size is $\overline{x} = 0.54$ and the TAC (or the TAFC for the FQ-system) is *H*=0.2 and that fisher *i* has a share (division) $d^i = 0.01$ of the total catch.

Figure 3 shows the marginal profit for fisher *i* as a function of his choice of the high-grading limit price p_b^i for the NQ constraint and for the FQ system for various subsidy parameters. Where the different curves cross the *zero* line, is his optimal choice of p_b^i, which is the price indicated in the legend. Also indicated is how much of the actual catch is discarded relative to the landed catch (equation 4.11). The numbers in this model with linear cost are independent of the size of the quota, but will increase with an increasing standard deviation $\sigma_{p^i}^i$ and/or an increasing profit margin ($\overline{p}^i - \frac{c}{\overline{x}}$).

For the FQ system, what is happening, is that the inclusion of the individual mean landing price in the penalty function works as a bootstrapping mechanism. The fisher will be able to high-grade the income part of his profit function by increasing the individual mean price $\overline{p}_g^i$, but the penalty will increase more since accumulated harvest is squared. If the individual mean price $\overline{p}_g^i$ was not included in the penalty function or if it was not individual (e.g. the mean price for all fishers), then the economic incentive for high-grading would be the same as for the NQ-system.

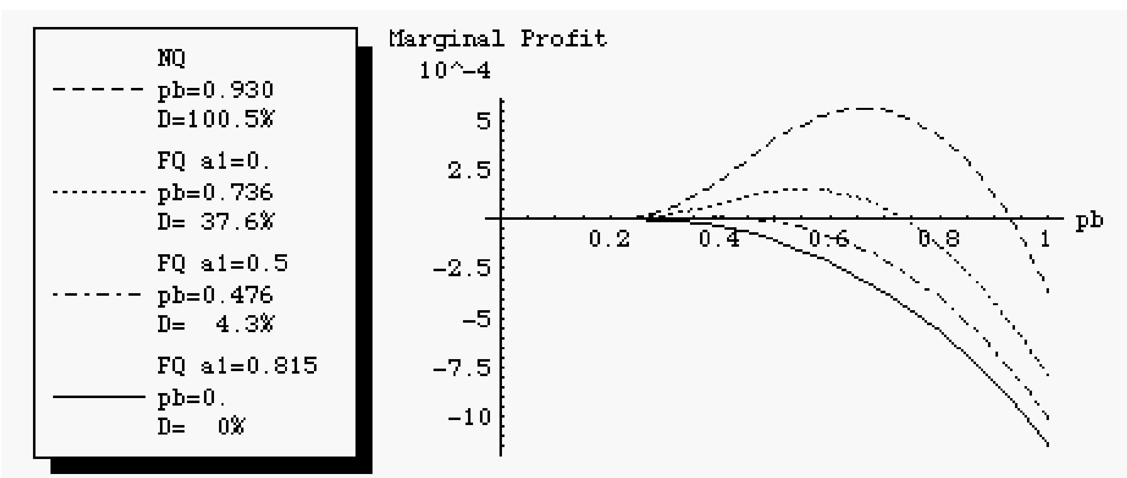


Figure 3. Marginal Profit as function of high-grading price p_b

5. Individual Transferable Flexible Quotas (ITFQs)

When FQs 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 fixed costs and denoting *p* as the constant market price for fish, the profit function for fisher *i* is

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

where *m* is the market price of an ITFQ unit and *H* is the total actual catch 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 (5.1) 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

(5.2) $$d^i = H^i\sqrt{\frac{pa_2}{2mH}}$$

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

(5.3) $$1 = \sum_i d^i = \sum_i H^i\sqrt{\frac{pa_2}{2mH}} = H\sqrt{\frac{pa_2}{2mH}} = \sqrt{\frac{pa_2 H}{2m}}$$

Hence, we find the following relationship between total catch *H*, market price *p*, quota price *m* and the a_2 regulation parameter

(5.4) $$H = \frac{2m}{pa_2}$$

Using this relationship, equation (5.2) becomes

(5.5) $$d^i = \frac{pa_2}{2m}H^i$$

The equation retained from setting the partial derivative of (5.1) w.r.t. H^i to *zero* determines fisherman *i*'s choice of output. When (5.5) is used the equation becomes

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

In a "normal" ITQ system the corresponding equation is (Clark, 1985)

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

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:

(5.8) $m = \dfrac{a_1 + q}{2}$

That is, if for example the a_1 subsidy parameter was set equal to *zero*, the FQ price *m* would be half of the price *q* of a NQ. 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

(5.9) $p\dfrac{a_2}{2d^i}\left(H^i\right)^2 - a_1 H^i$

Substituting d^i in this equation with (5.5) and simplifying yields

(5.10) $\left(m - a_1\right)H^i$

Since H^i is positive, the budget can only be *zero* if $a_1 = m$ and when this result is put into (5.8) one finds the following relationship

(5.11) $a_1 = m = q$

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 FQ share in a ITFQ system and these will also be equal to the price for a NQ share in the corresponding ITQ system.

6. Summary and perspective

The concept of individual flexible quotas (FQs) 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 (NQ) is defined as a private property right, one has to grasp the idea of an individual flexible quota as another type of private property right. Both concepts are management tools for centralized resource control, but while NQs in principle (or in its pure form) also centralizes individual catch decisions, FQs principally decentralize them.

One of the reasons for the FQ 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 NQs 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 this becomes 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 profit is charged by the regular public taxation system through a linear tax. If desirable one could charge all or a part of the same public tax through the FQ system and achieve a subsidy parameter that is lower than with the "*zero* exact catch budget"- condition. However since, for reasons mentioned in section 2, a lump sum subsidy is not desirable, there will be a lower limit on a_1. The advantage from a low a_1-value is a higher expected value and a lower standard deviation of recruitment after harvesting and lesser probability of extinction. On the other hand, a high value of the a_1-parameter will give less economic incentives for high-grading. The final choice is a matter of judgement.

Traditionally, harvesting rights (NQs) have been allocated to participants of the harvesting sector only. Matulich, 1998, argues for the need also to allocate processing rights to the processing sector to achieve a efficient solution, the so called two-pie allocation of rights. For a management system built with the FQ 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 FQ concept can favorably be used for regulation of several types of stock. Vessels opting for diverse fishing will get several FQs, and there will be an FQ 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 FQs allows for extensions above quotas and because fishing will not be aborted. Whereas NQ 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 switch-over period, costs may be more excessive at first.

Lots of problems in need of solutions will of course surface as one goes along and many clarifications will have to be made in connection to the practical implementation of a management system based on FQs. To get such a regulatory regime going, one has to pass through a learning phase both for fishers and managers. Since there is no knowledge on how fishers will react to increased marginal costs and there is little information available on the extent of aggregated marginal cost today, it would be wise to plan the first try-outs as experiments where the goal is to gather as much as possible of the needed information. This is feasible through the system itself because actual catches in this regime will expose a point on the marginal cost curves for individual vessels. For example FQs should not be allowed to be transferable at first because this might outshadow other important information. As a precautionary measure try-outs should also initially be kept on a lower scale, that is, with a low number of fishermen involved. It would be better to do parallel experiments at independent locations for example with different subsidy parameters.

The fishermen involved in the initial try-outs should be volunteers because access to their private account books might be desirable and they have to be "bothered" with for example interviews about how their decisions are influenced by the regulation. It might be possible that fishermen involved in the initial try-outs will be influenced by other fishers that are not involved. Therefore, even if the system appears to be favorable, any further implementation of the system should be made in small steps.

The FQ concept is not only flexible in the way that quotas are flexible, but within the shaping of management systems based on FQs there is a whole spectre of immanent possibilities. The best argument for trying it out is that it can confidently be asserted that the alternatives, the present-day regulatory systems, do not function very well. A project that starts up with the planning and ends up with practical try-outs of the system would be very informative, and the number of additional ideas for the development of prospective resource management models will certainly escalate.

References:

Clark C.W., 1986, "Bioeconomic Modeling and Fisheries Management", John Wiley & Sons, New York

Clark C.W., Kirkwood G.P., 1986, "On Uncertain Renewable Resource Stocks: Optimal Harvest Policies and the Value of Stock Surveys", *Journal of Environmental Economics and Management*, Vol. 13, pp. 235-244

Gillis, D.M., Peterman, R.M,, and Pikitch, E.K., 1995, “Dynamic discarding decisions: foraging theory for high-grading in a trawl fishery”, *Behavioral Ecology*, Vol. 6, pp. 146-154

Matulich, S.C., Sever, M., 1998, “Efficiency and Equity Implications of Alternative Transferable Quota Allocations Under Bilateral Monopoly”, IIFET’ 98 Proceedings, Tromsø, Vol. 1, pp. 188-196

Reed W.J, 1979, "Optimal Escapement Levels in Stochastic and Deterministic Harvesting Models", *Journal of Environmental Economics and Management*, Vol. 6, pp. 350-363