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Implications of Harvesting Strategies on Population and Profitability in Fisheries

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Abstract *The effects of different harvesting strategies on the mean and variation in size of the fish stock and net revenues are investigated. The strategies analyzed are constant catch, constant effort, and constant escapement. A Gordon-Schaefer model affected by cyclical disturbances and stochastic disturbances is applied. Factors explaining the differences between the strategies are the length of the recruitment cycles and the presence of stochasticity. With short recruitment cycles the constant catch strategy somewhat surprisingly produces least variation and highest mean with respect to stock size and net revenue, while constant escapement produces most variation and lowest mean. With longer recruitment cycles or pure stochasticity, constant escapement produces highest average stock size and net revenue as well as lowest variation in the stock size, but not in the net revenue. Constant effort is in most cases ranked between the other two strategies.*

Key words Aggregated fisheries models, bioeconomic modeling, harvesting strategies.

Introduction

As fluctuations due to environmental and ecological causes are prevalent in most fish stocks, minimization of the effects of such fluctuations upon the economic activity is regarded as important. This paper will take a look at how the choice of harvest management strategy may affect stability with respect to both economy and biology. Harvest management strategy refers to the reference points the managing authority chooses when it decides upon harvesting quotas. Three such strategies will be dealt with here: constant target escapement, constant fishing effort, and constant catch. These three strategies are among the most common reference points for fish stock management (Ricker 1958; Lett and Doubleday 1976; Beddington and May 1977; Getz, Francis, and Swartzman 1987). Note, however, that in all three cases actual management is performed by setting quotas such that no direct control of effort is required.

Two kinds of stability will be dealt with: minimization of variations in net revenue from the fishery and minimization of variations in the biomass of the fish stock. The reason why stabilization of net revenue is important is evident: fishermen are usually risk-averse and therefore prefer a stable income to a variable income

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with the same mean. The reason why stability in the fish population is desirable is also quite clear: it reduces the danger of stock-extinction and failing recruitment.

In addition to the variation in the fish stock and in the net revenue, the means of these variables are also analyzed. Other authors who have been concerned with the mean and the variance of harvest and profitability include Ricker (1958), Gatto and Rinaldi (1976), Horwood and Shepherd (1981), and Murawski and Idoine (1989). Usually they conclude that there is a trade-off between the mean and the variance of the harvest, and they rank constant catch as the strategy with the lowest mean, and constant escapement as the strategy with the highest mean. With respect to the variance of the harvest, the ranking is reversed. Constant effort is placed somewhere between the other two strategies in both respects. The same pattern is found when it comes to profitability when applying simple economic models with constant prices and constant costs. Reed (1979) is concerned with finding the optimal escapement policy in the presence of stochasticity, and he finds that this level is usually lower than the optimum derived from deterministic models. Also Pindyck (1984) is concerned with the risk premium imposed by stochastic fluctuations. Usually, constant escapement is found to produce least variation in the stock size while constant catch produces the most variation. Hopefully, this paper will shed some new light upon the ranking of the strategies, especially with respect to variations in the stock size.

The intent of the paper, however, is not to provide a realistic description of any single fish stock, but to investigate the consequences of different harvesting strategies with and without the presence of cyclical nature in recruitment. In this paper, a simple aggregated model with overlapping generations and a stock-recruitment relationship is applied to investigate these questions. As analytical results are hard to obtain, except in models without stock-recruitment relationships, numerical simulations are resorted to in most of the paper. In the numerical simulations, stylized facts from the Arcto-Norwegian cod-stock are used. Aggregated fisheries models can mainly be divided into two broad categories: surplus production models and recruitment models. A surplus production model is applied here as this is more realistic for the cod stock.

Emphasis is put on cyclical nature in recruitment. There are two main causes for cyclical nature. On the one hand there are environmental causes that are usually exogenous to the fish stock, and on the other hand, there are ecological causes. These include the stock's interaction with itself and with other stocks. One example is cannibalism. The explanation why cannibalism can cause cyclical nature is the following: a large stock sometimes results in a high degree of cannibalism. A high degree of cannibalism on immature fish, however, will harm the recruitment and thus reduce future stocks. A small stock will mean a lower degree of cannibalism which is good for recruitment and so on. The length of the cycles will depend upon the number of year-classes, and will therefore differ between species. Cannibalism increases with the scarcity of other prey items, and has in certain periods been high for cod (Nakken 1994). The same effects may be present when there are several interacting stocks, but the whole system then becomes more complex.

In models without stock-recruitment relationships, the length of the recruitment cycle and the degree of serial correlation in cyclical nature will decide the ranking of the strategies with respect to stability (Steinshamn 1992). This fact combined with the fact that cyclical nature in recruitment is present in many fish stocks [*e.g.*, Arcto-Norwegian cod (Hannesson and Steinshamn 1991)], has provided the motivation for this article. The hypothesis to be tested here is that the same is true for fish stocks with a stock-recruitment relationship.

Background and Motivation

The model outlined in this section lacks a stock-recruitment relationship and is only meant to serve as background and motivation for the rest of the paper. In the rest of the paper, a model with stock-recruitment relationship is applied. The following notation will be used: w_t = the escapement from the fish stock at time t; x_t = the biomass of the fish stock at time t; y_t = the harvest at time t; z_t = the fishing effort exerted at time t; $f(x_t)$ = the surplus production as a function of the biomass at time t; ρ_t = exogenous, stock independent[1] recruitment at time t; ε_t = the exogenous disturbance affecting the reproduction of the fish stock at time t; π_t = the net revenue at time t; s = survival (and individual growth) parameter; q = a constant catchability coefficient; r = the intrinsic growth rate in the stock; K = the natural carrying capacity of the stock; a = parameter indicating the width of the range from which ε is drawn; p = price per unit harvest; and c = cost per unit effort.

The main idea behind this work was spurred by some analytical and numerical results based on a discrete time, aggregated biomass fisheries model with overlapping generations, but without a stock-recruitment relationship. The analytical results are as follows.

Assume that the dynamics of the fish stock biomass are given by the equation

$$x_{t+1} = sw_t + \rho_t.$$

This is not meant to be a realistic representation of any fish stock, but is only meant to serve as a reference and background for further study. The survival parameter s accounts both for natural mortality and individual growth. Escapement at time t is defined as

$$w_t = x_t - y_t. \tag{1}$$

Note that this definition of escapement may be different from some other definitions. Assume further that the harvest in the fishery is given by the Cobb-Douglas-like production function

$$y_t = qz_t^{\gamma_1} x_t^{\gamma_2} \tag{2}$$

and that the recruitment ρ_t is given by an n-point cycle which is independent of the stock or the escapement. As effort is measured in arbitrary units, the effort in the model can be rescaled such that $q \equiv 1$. The parameters γ_1 and γ_2 will usually, but not necessarily, be less than one. Choosing high γ_1 and γ_2 will stress the differences between the harvesting strategies. If $\gamma_2 = 0$, then constant effort is equivalent to constant catch as catch is proportional to effort. Therefore, $\gamma_1 = \gamma_2 = 1$ in the rest of this paper. This implies $0 \leq z \leq 1$. Note that effort is defined as equivalent to the rate of harvest which is the same as the average fishing mortality during the period. In other words z is not a measure of the actual physical effort exerted, but rather some conceptual effort. Other production functions have been examined, and the results in this paper are not dependent on the particular choice of production function.

The dynamics of the fish stock with the three strategies—constant harvest, constant effort, and constant escapement—are given by the equations

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[1] By stock independent, recruitment is simply meant that it is not possible to find any significant statistical relationship between stock size and recruitment, *e.g.*, because it is the survival of the eggs and not the number of eggs that determines subsequent recruitment.

$$x_{t+1} = s(x_t - y) + \rho_t \tag{3}$$

$$x_{t+1} = sx_t(1 - z) + \rho_t \tag{4}$$

$$x_{t+1} = sw + \rho_t \tag{5}$$

respectively, where y, z, and w without subscripts are constants.

The shortest imaginable recruitment cycle is given by $n = 2$. In this case the recruitment sequence is given by

$$\rho_t = \frac{\rho_1 + \rho_2}{2} + \frac{\rho_2 - \rho_1}{2}(-1)^t .$$

The stock sequence in the case of constant catch can be found by solving the first-order difference equation

$$x_{t+1} - sx_t = -sy + \frac{\rho_1 + \rho_2}{2} + \frac{\rho_2 - \rho_1}{2}(-1)^t$$

and in the case of constant effort, by solving

$$x_{t+1} - s(1 - z)x_t = \frac{\rho_1 + \rho_2}{2} + \frac{\rho_2 - \rho_1}{2}(-1)^t .$$

The solutions of these two equations are given by the limit cycles (or induced n-point cycles):

$$x(t) = k\, s^t + \frac{\rho_1 + \rho_2 - 2sy}{2(1 - s)} - \frac{\rho_2 - \rho_1}{2(1 + s)}(-1)^t .$$

and

$$x(t) = m[s(1 - z)]^t + \frac{\rho_1 + \rho_2}{2[1 - s(1 - z)]} - \frac{\rho_2 - \rho_1}{2[1 + s(1 - z)]}(-1)^t .$$

respectively, where k and m depend on some initial conditions. Both solutions are stable when $|s| < 1$. From these two solutions it can be seen that the standard deviation of the stock in the case of constant catch in the long-run is

$$\frac{|\rho_1 - \rho_2|}{2(1 + s)}$$

and in the case of constant effort,

$$\frac{|\rho_1 - \rho_2|}{2[1 + s(1 - z)]} .$$

In the case of constant escapement, the standard deviation of the stock in the long-run is the same as the standard deviation of recruitment:

$$\frac{|\rho_1 - \rho_2|}{2}.$$

As $0 < s < 1$ and $0 < z < 1$ (because $q \equiv 1$), it is seen that

$$\frac{|\rho_1 - \rho_2|}{2} > \frac{|\rho_1 - \rho_2|}{2[1 + s(1 - z)]} > \frac{|\rho_1 - \rho_2|}{2(1 + s)}. \tag{6}$$

In other words, the variation of the stock is greatest in the case of constant escapement and smallest in the case of constant catch. The same can be shown with respect to variation in net revenue from the fishery assuming a nonnegative net revenue in each period (Steinshamn 1993). It is interesting to note that the result given by the inequalities in expression (6) applies to all possible values of y, z, and w.

Define admissible catch as catch that adheres to the constraint[2]

$$y_t < \min[x_1, \ldots, x_n] \;\; \forall \;\; t. \tag{7}$$

Even the greatest admissible level of the constant catch yields less variation in the biomass than any level of the constant escapement. This is due to the fact that the variation of the stock with constant catch is independent of the size of the catch and equal to the variation in the stock biomass without harvesting. The variation of the stock size with constant escapement, on the other hand, is equal to the variation of the recruitment. This will be greater than the variation of the stock without harvesting assuming $0 < s < 1$, that is assuming overlapping generations. A survival rate, $s = 0$, corresponds to nonoverlapping generations. The constant effort strategy will always produce a variation which lies between the other two strategies.

Using the same procedure it can be shown analytically that these results also apply to the cases $n = 3$ and $n = 4$. For higher values of n, however, the ranking of the strategies with respect to variation in the stock may be reversed. Using numerical methods, it has been shown that the higher n, the higher the probability of reversal of the ranking of strategies, see Steinshamn (1992).

The model studied so far does not include any stock-recruitment relationship. This is not very realistic. And if there is no such relationship, why should stabilization of stock size be of any concern when future recruitment is not affected by it? Obviously, the reason for presenting these results is that they indicate some implications of different harvesting strategies, and it would be interesting to see if they also apply to other models that include stock-recruitment relationships. The next section explores that question.

[2] For any n this constraint can be written

$$y_t < \frac{s^{n-1}\rho_j + s^{n-2}\rho_{j+1} + \ldots + s^{n-j}\rho_n + s^{n-j-1}\rho_1 + \ldots + s^0\rho_{j-1}}{s^{n-1} + s^{n-2} + \ldots + 1}$$

where $\rho_j = \max\{\rho\}$.

A Surplus Production Model

In this section, a Gordon-Schaefer model combined with Monte-Carlo simulations is applied. The function for the fish stock dynamics is given by the equation

$$x_{t+1} = x_t - y + f(x_t)\varepsilon_t. \tag{8}$$

Escapement is defined as in equation (1) and harvest is given by the production function $y_t = x_t z_t$. Net revenue at time t is defined by

$$\pi_t = py_t - cz_t.$$

We look at four different cases with respect to the exogenous variable $\varepsilon(t)$. As cyclical nature is of major concern in this paper, three cases with deterministic n-point cycles are investigated. These are four year cycles, eight year cycles, and twelve year cycles. In addition, the case of $\varepsilon(t)$ as a purely random variable is considered. It is assumed in all simulations that the respective strategies are implemented for a period of twenty-four years; that is, the time horizon, T, is 24.

The objective then is to find the standard deviation and the mean of x and π when the standard deviation of ε and the length of the recruitment cycle, n, are varied. The starting point (initial stock) for each strategy is the undiscounted optimal steady state when $\varepsilon(t) = 1$ for all t which is the same for all strategies.

In the case of deterministic n-point cycles, the sequence $\{\varepsilon_n\}$ is given by

$$\varepsilon_t = a \sin\left(\frac{2\Pi t}{n}\right) + 1, \quad t = 1, ..., 24. \tag{9}$$

In this case the standard deviation of ε is increased by increasing the range of ε through increasing a. The width of the range of ε is $2a$ and the mean of ε is 1. The formulation in equation (9) has been chosen here because it is the simplest possible way to represent the kind of cyclical nature wanted.

In the case with purely random disturbances, twenty-four random numbers are drawn from a uniform distribution with expectation 1 and range $[1 - a, 1 + a]$. Again the standard deviation of ε is reported and it is increased by increasing a. The width of the range of ε is $2a$. In this paper $a = 0.1$ is referred to as the case where the degree of stochasticity is ±10% (low stochasticity), and $a = 0.5$ is referred to as the case where the degree of stochasticity is ±50% (high stochasticity). A 50% stochasticity level is considered sufficiently high to cover all realistic cases for the Arcto-Norwegian cod. The uniform distribution has been chosen instead of the normal or lognormal in order to emphasize the differences between the strategies.

The deterministic equivalent of the model is defined by $\varepsilon_t = 1$ for all t. In the deterministic equivalent model the steady state is defined by $y = f(x)$.

With these assumptions, the sequences (or vectors) of x- and π-values with the respective harvesting strategies are derived as follows. The sequences for x and π with the constant catch strategy are found by solving:

$$f(x_1) = y^* \equiv \frac{r}{4}\left(K - \frac{c^2}{p^2 q^2 K}\right) \tag{10}$$

$$x_{t+1} = x_t - y^* + f(x_t)\varepsilon_t, \quad t = 1, ..., 23$$

$$\pi_t = py^* - c\,\frac{y^*}{x_t}.$$

The sequences for x and π with the constant effort strategy are found by solving

$$\frac{f(x_1)}{x_1} = z^* \equiv \frac{r(pqK - c)}{2pq^2K} \tag{11}$$

$$x_{t+1} = x_t(1 - z^*) + f(x_t)\varepsilon_t, \quad t = 1, ..., 23,$$

$$\pi_t = px_t z^* - cz^*.$$

The sequences for x and π with the constant escapement strategy are found by solving

$$x_1 - f(x_1) = w^* \equiv \frac{(pqK + c)(2pqK - rpqK + cr)}{4p^2q^2K} \tag{12}$$

$$x_{t+1} = w^* + f(x_t)\varepsilon_t, \quad t = 1, ..., 23,$$

$$\pi_t = p(x_t - w^*) - c\frac{x_t - w^*}{x_t}.$$

The constant values y^*, z^*, and w^* are the undiscounted optimal steady states based on a deterministic model with $\varepsilon_t = 1$ for all t. In the numerical analysis, interest will be concentrated on how much variation the variable ε produces in the biological and the economic submodels under the different strategies. Variation in the biological submodel is simply defined as the standard deviation of the sequence of x. Variation in the economic submodel is defined as the standard deviation of the sequence of π. In addition, the means of x and π are reported.

Numerical Results

The numerical results presented here are based on a Gordon-Schaefer model which is characterized by the function

$$f(x) = rx\left(1 - \frac{x}{K}\right) \tag{13}$$

measured in million tonnes. The numerical specification of the parameters r and K have been adjusted to match the stylized facts about the Arcto-Norwegian cod stock in Flaaten (1988). The values for p and c have also been taken from Flaaten: $r = 0.35$ (dimensionless), $K = 8.26$ (million tonnes), $p = 5.10$ (billion NOK), and $c = 9.1452$ (billion NOK). A constant price is justified here because more than 90% of the harvest is exported and sold at a fixed international price.

With respect to length of the deterministic recruitment cycle, three alternatives will be considered: $n = 4$, $n = 8$, and $n = 12$. These sequences are produced according to equation (9). In addition the alternative of completely random disturbances referred to above, where the vectors of ε values are random vectors drawn from a uniform distribution, is considered.

In the case with $\varepsilon(t) = 1$ for all t, the three strategies coincide with respect to optimal stock size and corresponding profitability. In other words, y^*, z^*, and w^* all represent the same optimal policy. These values are therefore used as reference points in the stochastic model. The optimal target values are slightly different when there is stochasticity, but the results presented in the following are not sensitive to this particular choice of target values, nor are they sensitive to variations in the parameter values. With the parameter values used here $y^* = 0.689$, $z^* = 0.137$, and $w^* = 4.34$. The variables y and w are measured in million tonnes whereas z is dimensionless. These values are used as constant catch, constant effort, and constant escapement in equations (10), (11), and (12) respectively.

In the following, numerical simulations based on this model are reported. First, three different recruitment cycles of length four years, eight years, and twelve years are investigated. For each cycle two different amplitudes are used with respect to the variable ε, namely ±10% variation and ±50% variation. In addition Monte Carlo simulations are performed based on 2,000 sequences of the random vector ε drawn from a uniform distribution. Also in this case, two degrees of stochasticity are applied, namely $\varepsilon \in [0.9, 1.1]$ and $\varepsilon \in [0.5, 1.5]$. Based on these 2,000 simulations, empirical 95% confidence intervals are found for the mean and the standard deviation of stock and net revenue. The standard deviation of the variable ε is also reported. In addition the question about sustainability of each of the strategies is considered. A strategy is considered here as sustainable over the period if the stock in period $T + 1$, that is in period 25, is higher than the Maximum Sustainable Yield (MSY) stock level. The MSY stock level is here given by $x_{MSY} = K/2 = 4.13$. This condition for stability or sustainability represents a rather strong requirement as most fish stocks in the world today are far below the MSY level. The calculated confidence intervals are based on all the 2,000 simulations and not only the “sustainable” ones. It must also be mentioned that none of the simulations resulted in inadmissible catches defined as $x_t < y$ in any period.

Reproduction Cycle of Length n = 4

First a reproduction cycle of four periods is applied. The results from this model are reported in table 1. From table 1 it is seen that constant catch produces the lowest variation in both stock size and net revenue with 10% variation in ε as well as 50%. This result with respect to variation in stock size which occurs with short cycles, is quite interesting and counterintuitive. Constant escapement produces most variation in both stock size and net revenue. When it comes to mean stock size constant catch results in the highest mean whereas constant escapement results in the lowest mean. With respect to the mean net revenue, constant effort yields the highest mean and constant escapement yields the lowest mean although the difference between constant effort and constant catch is quite small.

Reproduction Cycle of Length n = 8

In this section the reproduction cycle is doubled, that is $n = 8$. A recruitment cycle of length eight is interesting because evidence from empirical studies of the Arcto-Norwegian cod stock indicates a recruitment cycle of this length, see Hannesson and Steinshamn (1991). Table 2 is analogous to table 1.

It is first noted that constant catch produces least variation in net revenue whereas constant escapement produces most variation as earlier. This is a steadfast result. When it comes to variation in the stock size, things have changed. Now constant escapement produces least variation in stock size and constant effort produces most variation. With respect to the mean of the stock size and profitability, the ranking of the strategies is as earlier. Constant catch produces the highest mean stock and constant effort produces the highest mean profit. Constant escapement has the lowest mean with respect to both variables.

Table 1
Standard Deviation and Mean of Stock Size and
Net Revenue With Cyclical Disturbances When n = 4

		St.D. (x)	St.D. (π)	Avg. (x)	Avg. (π)	St.D. (ε)
10%						
	Constant catch	0.037	0.009	5.043	2.263	0.071
	Constant effort	0.039	0.027	5.033	2.264	0.071
	Constant esc.	0.049	0.171	5.026	2.259	0.071
50%						
	Constant catch	0.181	0.044	5.118	2.280	0.353
	Constant effort	0.195	0.136	5.065	2.286	0.353
	Constant esc.	0.243	0.856	5.023	2.265	0.353

Notes: ε is calculated according to equation (9) with t = 1, ..., 24. The variation in ε is ±10% and ±50%.

Table 2
Standard Deviation and Mean of Stock Size and
Net Revenue with Cyclical Disturbances When n = 8

		St.D. (x)	St.D. (π)	Avg. (x)	Avg. (π)	St.D. (ε)
10%						
	Constant catch	0.069	0.017	5.063	2.268	0.071
	Constant effort	0.071	0.050	5.041	2.269	0.071
	Constant esc.	0.046	0.163	5.026	2.259	0.071
50%						
	Constant catch	0.340	0.081	5.184	2.292	0.353
	Constant effort	0.354	0.247	5.080	2.297	0.353
	Constant esc.	0.230	0.810	5.019	2.251	0.353

Note: ε is calculated according to equation (9) with t = 1, ..., 24. The variation in ε is ±10% and ±50%.

Reproduction Cycle of Length n = 12

It will now be interesting to see whether the results derived from increasing the reproduction cycle from four to eight is reconfirmed when the cycle is further increased, this time to twelve years. The result that constant escapement produces relatively more variation in stock size for short recruitment cycles is of particular interest. The results when n = 12 are reported in table 3.

Constant catch and constant effort show quite similar values both with respect to mean profit and variation in stock size. Constant escapement, on the other hand, has lower mean profit and lower variation in stock size than the other two. In other words, the result from earlier has been reconfirmed. The rankings with respect to mean stock size and variation in profit, that constant catch has highest mean stock and lowest variation in profit, while constant escapement has the opposite, have been reconfirmed.

From this analysis it seems that the length of the reproduction cycle is important, especially with respect to variation in stock size. The longer the reproduction cycle, the lower the variation in stock size caused by constant escapement relative to the other two strategies. Constant catch, on the other hand, produces least variation

Table 3
Standard Deviation and Mean of Stock Size and
Net Revenue with Cyclical Disturbances When n = 12

		St.D. (x)	St.D. (π)	Avg. (x)	Avg. (π)	St.D. (ε)
10%						
	Constant catch	0.101	0.025	5.081	2.272	0.071
	Constant eff.	0.100	0.070	5.045	2.272	0.071
	Constant esc.	0.046	0.161	5.026	2.259	0.071
50%						
	Constant catch	0.503	0.121	5.214	2.293	0.353
	Constant eff.	0.497	0.348	5.075	2.293	0.353
	Constant esc.	0.228	0.801	5.019	2.249	0.353

Note: ε is calculated according to equation (9) with t = 1, ..., 24. The variation in ε is ±10% and ±50%.

in net revenue and highest mean stock whereas constant effort produces highest mean profit. The next question is whether these results also occur when the disturbances are no longer cyclical but randomly distributed. In order to answer this, Monte Carlo simulations are used.

Monte Carlo Simulations

In this section 2,000 sequences of 24 values of the random variable ε have been drawn from a uniform distribution. A uniform distribution has been chosen in order to accentuate the differences between the strategies. Two different levels of stochasticity are applied. That is, the first 2,000 sequences are drawn when $\varepsilon \in [0.9, 1.1]$ and then 2,000 sequences are drawn when $\varepsilon \in [0.5, 1.5]$. The same sequences are of course used for all three strategies, and based on these simulations, empirical confidence intervals for the mean and standard deviation of net revenue and stock size are established. The question about stability or sustainability of the strategies has been handled by defining a simulation as unstable if the stock size in period $T + 1$, that is period twenty-five, is lower than the MSY stock level. The number of simulations where this requirement is not fulfilled has been reported in table 4, but these simulations have *not* been removed from the analysis. The empirical confidence intervals at the 95% significance level are given in table 4 together with the average values.

It is seen from table 4 that with the lowest level of stochasticity (±10%) there is hardly any difference between the strategies with respect to average stock size and profitability. With respect to the variation, constant catch produces highest variation in stock size and lowest variation in profitability, whereas constant escapement produces highest variation in profitability and lowest variation in stock size based on the average values. Based on the confidence intervals, there is no significant difference between the strategies at the 95% level, as the intervals are overlapping with exception of the variation in profitability with constant escapement.

When the degree of stochasticity is increased to ±50%, constant escapement comes out as the strategy with highest stock size and profitability and lowest variation in stock size. Constant catch is still the strategy with lowest variation in profitability based on the average values. Based on the confidence intervals, the only difference between the strategies that is significant at the 95% level, is again the high variation in profitability with constant escapement.

Table 4
Standard Deviation and Mean of Stock Size
and Net Revenue With Random Disturbances

	St.D. (x)	St.D. (π)	Avg. (x)	Avg. (π)	St.D. (ε)	Unstable
10%						
Constant catch	0.060 [0.033, 0.103]	0.015 [0.008, 0.026]	5.03 [4.89, 5.14]	2.26 [2.22, 2.29]	0.0602	0
Constant effort	0.051 [0.032, 0.078]	0.035 [0.022, 0.054]	5.03 [4.96, 5.08]	2.26 [2.21, 2.30]	0.0602	0
Constant esc.	0.038 [0.030, 0.046]	0.135 [0.106, 0.161]	5.03 [5.01, 5.04]	2.26 [2.21, 2.31]	0.0602	0
50%						
Constant catch	0.306 [0.166, 0.568]	0.083 [0.040, 0.191]	4.98 [4.21, 5.54]	2.23 [2.00, 2.37]	0.301	204
Constant effort	0.252 [0.161, 0.391]	0.176 [0.112, 0.273]	5.01 [4.68, 5.32]	2.25 [2.02, 2.46]	0.301	8
Constant esc.	0.191 [0.152, 0.226]	0.673 [0.536, 0.797]	5.03 [4.95, 5.10]	2.27 [2.01, 2.53]	0.301	0

Note: Average values and empirical 95% confidence intervals are based on 2,000 observations. The range of ε is ±10% and ±50%.

When it comes to the stability or sustainability of the strategies, all strategies are sustainable with the lowest level of stochasticity in the sense that even after the strategy has been in place for twenty-four years, the stock size has not dropped below the MSY stock level. When the level of stochasticity is increased to ±50%, this is no longer true. Now the stock size in period $T + 1$ is below the MSY level in 204 of 2,000 cases (10% of the cases) with constant catch in 8 of 2,000 (0.4% cases) with constant effort. There are no instances of inadmissible catch in the sense that the stock level is lower than the catch quota in any of the simulations. This leads us to believe that all three strategies are reasonably sustainable with respect to this particular fish stock. In general, it is in most cases possible to adopt an adaptive approach to quota management and reduce the target as soon as the stock size falls below the MSY level (or any other reference level) irrespective of what strategy is being used.

Implications for Management

This section examines the policy implications of the results. A sole owner of the fish stock, or rather, a managing authority acting as a sole owner, is assumed. This means that problems related to inefficiency and overcapacity may be disregarded. Further, it is assumed that the objective of the managing authority is not only to maximize the economic rent, but also to secure stable conditions for the fishermen. Stability in this context is twofold. It refers to stable economic conditions in the form of stable income, and it also refers to stable biological conditions in the form of a stable fish stock. A highly variable fish stock may affect the economy because the cost of harvesting varies with the size of the stock. In the present analysis this is seen directly from equation (2) assuming that costs are increasing in effort, z. High variability in the fish stock also concerns the sustainability of the fishery because low stock sizes may harm future recruitment and thus impose undue risk.

What implications do the results derived here have with respect to choice of harvest management strategy? The answer depends on the kind of fish stock in question. The most important characteristics of the fish stock in this regard are the presence of cyclical nature or stochasticity in the recruitment process, and, in the case of cyclical nature, the length of the cycle.

Another important factor is the length of the life span of the species in question. In the model presented in the Background and Motivation section, in which recruitment is independent of spawning stock size, the length of the life span is reflected through the survival parameter s. A high s means that a large proportion of the population survives from one period to the next, and thus reflects a long-lived species. It is clear from equation (4) that higher constant effort is equivalent to a smaller s. For stocks with overlapping generations, a constant effort, z, close to zero means that constant effort more or less coincides with constant catch, whereas a z close to one means that constant effort coincides with constant escapement in the sense that they produce similar dynamics. For stocks with nonoverlapping generations, *i.e.*, when s equals zero, the dynamics of the three strategies are identical. The implication of this is that for very short-lived species the choice of strategy becomes less important. For stocks with nonoverlapping generations, the choice of strategy is irrelevant with this model. A constant catch strategy, however, may be impossible to implement in this case. When the species is short-lived, but nevertheless a certain proportion of the stock survives from one period to the next, a constant escapement strategy is probably recommended because this is the strategy that minimizes risk.

This means that the constant effort or constant catch strategies should only be considered in the case of fish stocks with a life span of a certain length based on the model described in the Background and Motivation section. Constant catch should only be recommended for rather long-lived species. What particular strategy should be chosen then for such long-lived species? This depends on the degree of cyclical nature and the degree of stochasticity. Whether these phenomena are present or not, and to what degree, is an empirical question. The important aspects are the length of possible cycles and the degree of cyclical nature relative to pure stochasticity. If short cycles can be safely demonstrated, there is no reason why constant catch should not be recommended when stability is of high priority to the managers. For longer cycles, and in the presence of purely random disturbances, the constant escapement strategy should be recommended just as it should in the case of short-lived species unless high priority is put on the variation in net revenue which always is quite high with this strategy.

As demersal species like cod and haddock usually have longer life spans than pelagic schooling species like capelin and herring, the constant catch strategy should primarily be reserved for demersal species. Constant effort and constant escapement, on the other hand, may be applied both to demersal and pelagic species.

Another argument is that constant escapement usually yields a higher average return than the other two strategies, and that constant effort yields a higher return than constant catch. This is true for the average catch measured in biomass, and there is therefore a trade-off between the average catch and the variation in the catch. When it comes to economic return, however, the ranking of strategies may be different. As higher stock size usually means lower costs, the ranking may be reversed. Also when downward sloping demand curves or increasing marginal costs are taken into account, it is no longer obvious which strategy produces the highest economic return. The slope of the demand curve and the degree of increasing marginal costs are empirical questions. For a discussion of some theoretical aspects of downward sloping demand and increasing marginal costs, see Steinshamn (1993).

Parameter values different from those reported in this paper have been examined, and the overall conclusions are not at all sensitive to changes in the parameters. Nor are the conclusions sensitive to reasonable changes in the functional forms of the production function (2) or the growth function (13). This means that the results can be transferred to other fisheries than the Arcto-Norwegian cod fishery which has been used here as an example.

Summary and Conclusions

The main conclusion to be drawn from this analysis is that the implications of the harvesting strategies with respect to variation and the mean of stock biomass and net revenue derived on the basis of a model without a stock-recruitment relationship are also present in the models that include these relationships.

The implications with respect to the stock biomass are that with short recruitment cycles, $n \leq 4$, a constant catch will produce least variation in the biomass, whereas a constant escapement strategy will produce most variation. This is a quite interesting and counterintuitive result. For recruitment cycles of medium length, $n = 8$, the ranking of the strategies with respect to variation in biomass is reversed, and this result is reconfirmed when the recruitment cycle is further increased, *e.g.*, to $n = 12$. With a random disturbance variable, the ranking of the strategies seems to be the same as for long recruitment cycles, although it is hard to point out significant differences between the strategies at a 95% significance level except with respect to variation in profitability. The main conclusions are summarized in table 5.

The main implication these results have for management, is that when managers are concerned about the variation in the fish stock biomass and the variation in net revenue for fishermen, and not only in the highest possible yield in biomass, constant catch strategies and constant effort strategies may be good alternatives to constant escapement strategies in many cases. The main instances in which this is not the case are when recruitment cycles of a considerable length or with a high degree of stochasticity can be established, or in the case of managing short-lived species. It is an important fact that many, if not most, fish stocks around the world are characterized by a high degree of randomness in the recruitment process.

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Table 5
Summary of the Strategies With Respect to
Variation and Mean of Stock Size and Profitability

	Variation in x	Variation in π	Average x	Average π
Constant catch	Best with short cycles	Always best	Best with cyclicality	Intermediate
Constant effort	Intermediate	Intermediate	Intermediate	Best with cyclicality
Constant escapement	Best with long cycles	Always worst	Best with stochasticity	Best with stochasticity

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