Strategies for Stabilization: Constant Catch or Constant Fishing Effort?

Rognvaldur Hannesson
Norwegian School of Economics and Business Administration
Bergen, Norway

Abstract

Most fisheries are subject to substantial fluctuations in catches and fishing activity. There are obvious arguments for stabilization. Typically catches and fishing activity cannot be stabilized simultaneously. This paper considers the economic desirability of stabilizing catches versus fishing effort. The case when fishing mortality is proportional to effort is analyzed in some detail and it is shown that a stable effort is more profitable than stable catches, unless the price of fish depends on the catch volume. This is illustrated by quasi-empirical examples taken from two stocks of Atlantic cod.

Introduction

The management of fish stocks primarily is based on biological criteria. A time-honored criterion is the F_{max} or F_{01}; another is the target spawning stock criterion. Neither of these criteria take into account economic or social factors. Exactly how such factors should be taken into account can be debated. On strictly economic grounds, maximization of the present value of fishing rent would be the most appropriate criterion.[1]

[1] Fishing rent is the difference between revenue and cost, including capital cost. The rationale for maximizing fishing rent is due to the economic efficiency this implies. When fishing rent is maximized, a marginal unit of labor, capital, and other factors of production applied in the fishing industry produces a value equal to the cost of this unit. Provided the same is true for other industries, the value produced by a marginal unit of a factor of production will be the same in all industries, implying that no gains can be obtained by reallocating the factors of production.

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Other criteria based on economic considerations have been proposed from time to time. One such rule is stabilization of the catch. There are valid economic arguments for such stabilization. Fluctuating and unpredictable catches result in an uneven utilization of capacity and difficulties in maintaining markets, and make it difficult to plan the activity of the fishing industry. However, predictability and even capacity utilization also can be advanced in favor of stabilizing the activity of the fishing fleet. Since stabilization of the catch need not imply stabilization of the activity of the fishing fleet, the stabilization argument alone does not identify a unique management strategy.

In this paper, we make an economic comparison of these two policies—stabilization of catches and stabilization of the activity of the fishing fleet. We refer to the latter as fishing effort, without necessarily implying that it is synonymous with fishing mortality; however, for the most part, we shall assume that this is the case. We discuss which economic factors will favor stabilization of catch and effort; we use a simple numerical example to illustrate when stable catch will be superior to stable effort; we examine how the stabilization strategies might apply to real world fisheries, using two Atlantic cod stocks as examples; and we have a brief concluding section.

When Is Stable Catch More Profitable Than Stable Effort?

Let the catch of fish in time interval t be denoted by Y_t. The catch will depend on the size of the fish stock at the beginning of the interval, S_t, and the effort applied over the interval, Z_t:

$$Y_t = H(S_t, Z_t). \tag{1}$$

If it is desired to take a given catch, $\overline{Y}$, in every period, the effort generally will have to be varied according to the size of the fish stock at the beginning of each period:

$$Z_t = H^{-1}(S_t; \overline{Y}) = G(S_t, \overline{Y}). \tag{2}$$

The expected profit ($E\pi$) of the fishing industry in period t under the two fishing strategies, stable catch ($\overline{Y}$) and stable effort ($\overline{Z}$), is

$$E\pi = ER(Y_t) - C(\overline{Z}) = ER[H(S_t; \overline{Z})] - C(\overline{Z}) \tag{3a}$$

$$E\pi = R(\overline{Y}_t) - EC(Z_t) = R(\overline{Y}) - EC[G(S_t; \overline{Y})] \tag{3b}$$

where $R(\bullet)$ denotes revenue and $C(\bullet)$ is the cost of fishing. Note that stabilizing the catch stabilizes revenue, while stabilizing effort stabilizes cost. In general, the profit of the fishing industry will be unstable and uncertain under both strategies, except in one special case to be discussed below. Minimizing the variability of the profit most likely would imply some variation in both effort and the catch.

Which one of these involves the highest expected profit? We see that this depends on the shape of the revenue and cost function. If the revenue function is concave, as is likely, we have

$$R(\bar{Y}) > ER(Y), \bar{Y} = EY$$

that is, a catch stabilized at a level equal to the expected catch in the absence of stabilization will yield a higher revenue than the unstable catch, on average. A convex revenue function would yield the opposite result. The revenue function will be convex if the price elasticity of demand is constant and less than 1; that is, if a 1% reduction in quantity increases the price by more than 1%. The price elasticity of demand could be less than 1 if the fish from the stock under consideration is a major source of supply in the market.[2]

Now look at the fishing cost function. If the cost per unit of effort is constant, it will be a straight line, but if the cost per unit of effort rises with effort, which is by far more likely than the opposite, the cost of effort function will be convex. Then

$$C(\bar{Z}) < EC(Z), \bar{Z} = EZ$$

that is, the cost of effort stabilized at a level equal to the expected, variable effort will be less than the expected cost of the variable effort.

To sum up so far, cost considerations most likely will pull in the direction of stabilizing fishing effort. The results on the demand side are less clear-cut, but if the price of fish is not too sensitive to changes in the quantity supplied, the demand factors will argue in favor of stabilizing the catch.

At this point it is convenient to mention a special case. Suppose the catch depends only on fishing effort and is independent of the stock, as appears to be close to the truth for some pelagic, schooling stocks (Ulltang 1980; Bjørndal 1987). Stabilizing the catch will then amount to stabilizing the effort, and vice

[2] The revenue function will be convex if $R'(Y) < 0$ and $R''(Y) > 0$, with primes denoting first and second derivatives. With a constant elasticity of demand (η), the revenue function $R = P(Y)Y = Y^{1-1/\eta}$. This gives $R' = (1 - 1/\eta)Y^{-1/\eta} < 0$ if $\eta < 1$, and $R'' = -[(1 - 1/\eta)/\eta]Y^{-1-1/\eta} > 0$. The results based on a concave revenue function apply to maximizing the sum of consumer and producer surplus instead of revenue, since this is a concave function.

versa. A stable catch and effort will result in a stable profit, so equations (3a) and (3b) will be identical:

$$\pi = R(\bar{Y}) - C(\bar{Z}). \qquad (3')$$

Note that fishing effort is not proportional to fishing mortality in this case. If a constant share of the stock is harvested (constant fishing mortality), both catch and effort will vary with the stock, and so will the profit:

$$E\pi = ER(Y) - EC(Z).$$

A Numerical Example

Suppose we have a fish stock that varies at random, and the stock left behind in period t has no effect on the amount of fish available in period t+1. To simplify the exposition, suppose that the probability distribution of the values the stock can attain is independent of time, and that all values between the lower and the upper limit are equally probable. Let the stock be measured in units relative to its expected value, so that $ES = 1$. If the density of the stock is constant and equal to 1, the lower and upper limits are 0.5 and 1.5, respectively.

Let the production function $H(S,Z)$ be specified as[3]

$$Y = S(1 - e^{-z}) \qquad (4)$$

where it is assumed that Z is applied over the period of unit length, Y is the catch over the period, and S the size of the stock at the beginning of the period. No natural mortality is supposed to occur during the period, but at the end of the period, all the remaining stock disappears.

Suppose, further, that the price of fish is constant and equal to one, and that the cost per unit of effort is constant and denoted by w. Then the revenue and cost functions are both linear. The analysis in the previous section might entice us to believe that stable catch and stable effort would yield the same result. This is mistaken, however, as the following example demonstrates.

Since the density of fish is constant and equal to one, the expected profit will be

$$E\pi = \int_{0.5}^{1.5} S(1 - e^{-z})dS - wZ = (1 - e^{-z}) - wZ. \qquad (5)$$

[3] This production function pertains if the instantaneous fishing mortality is Z, if there is no natural mortality, and if the stock is fished for one time period with the fishing mortality Z.

Maximizing the expected profit with respect to effort implies

$$dE\pi / dZ = e^{-z} - w = 0. \tag{6}$$

From this we get

$$Z = -\ln w. \tag{7}$$

Inserting this in (5) gives

$$E\pi = 1 - w(1 - \ln w). \tag{8}$$

To deal with the case of stable catch, we must find the equation $Z = G(S;Y) = H^{-1}(S;Y)$. From (4) this is seen to be

$$Z = -\ln(1 - Y/S). \tag{9}$$

The expected profit is

$$\begin{aligned} E\pi &= Y + w\int_{0.5}^{1.5} \ln(1 - Y/S)dS \\ &= Y + w\{1.5\ln(1 - Y/1.5) - 0.5\ln(1 - Y/0.5) \\ &\quad + Y[\ln(0.5 - Y) - \ln(1.5 - Y)]\}. \end{aligned} \tag{10}$$

Maximizing the expected profit with respect to Y implies

$$dE\pi / dY = 1 + w[\ln(0.5 - Y) - \ln(1.5 - Y)] = 0. \tag{11}$$

From this we get

$$Y = \frac{1.5e^{-1/w} - 0.5}{e^{-1/w} - 1}. \tag{12}$$

Inserting this in (10) yields

$$\begin{aligned} E\pi = \frac{1.5e^{-1/w} - 0.5}{e^{-1/w} - 1} + w\Bigg[& 1.5\ln\left(1 - \frac{e^{-1/w} - 1/3}{e^{-1/w} - 1}\right) - 0.5\ln\left(1 - \frac{3e^{-1/w} - 1}{e^{-1/w} - 1}\right) \\ & - \frac{1.5e^{-1/w} - 0.5}{e^{-1/w} - 1}\ln\left(1.5 - \frac{1.5e^{-1/w} - 0.5}{e^{-1/w} - 1}\right) \\ & + \frac{1.5e^{-1/w} - 0.5}{e^{-1/w} - 1}\ln\left(0.5 - \frac{1.5e^{-1/w} - 0.5}{e^{-1/w} - 1}\right)\Bigg]. \end{aligned} \tag{13}$$

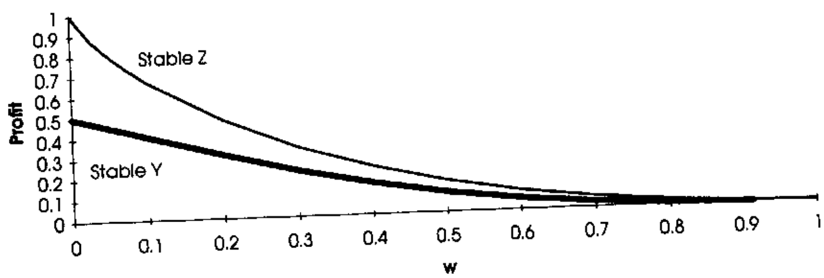

Figure 1. *The expected profit under two stabilization strategies as functions of the unit cost of effort.*

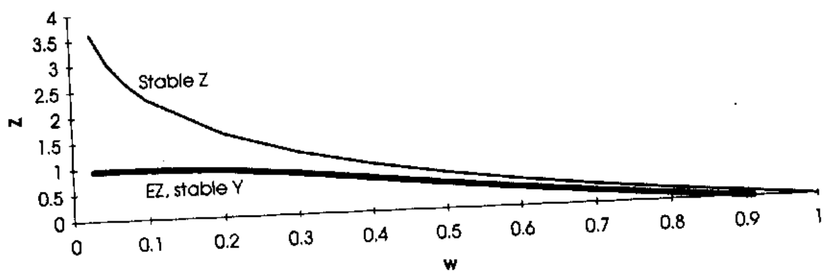

Figure 2. *For any given cost of effort, the expected effort for an optimum stable catch always is less than the optimum stable effort.*

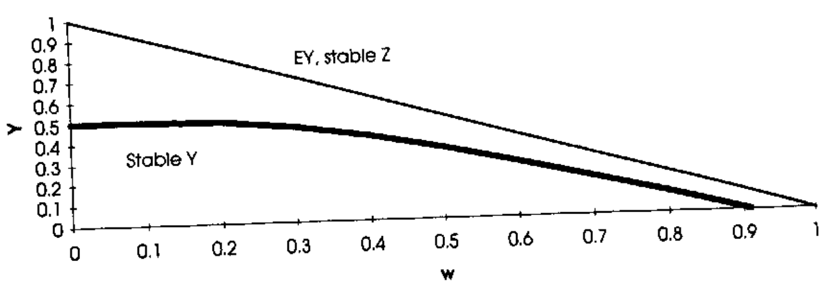

Figure 3. *The optimum stable catch always is less than the expected catch with optimum stable effort.*

Equations (8) and (13) show the expected profit under the two stabilization strategies as functions of the unit cost of effort (w). Figure 1 shows this graphically. The stable catch option gives a consistently lower expected profit than the stable effort option. Figures 2 and 3 show how optimal effort and catch depend on the unit cost of effort. As the unit cost of effort approaches zero, the optimum stable effort approaches infinity. For any given cost of effort, the expected effort for an optimum stable catch always is less than the optimum stable effort (Figure 2), and the optimum stable catch always is less than the expected catch with optimum stable effort (Figure 3).

One reason why the stable effort strategy gives a better result than the stable catch strategy, despite the linearity of the revenue and cost functions, is that the catch never can be stabilized at a higher level than the minimum level of the stock. (Remember that the stock size is assumed to be totally random.) As Figure 3 shows, the optimal stable catch reaches this level (0.5) for low values of w. This precludes taking advantage of a plentiful stock, which would be possible with the stable effort strategy. As w approaches zero, the optimum effort becomes arbitrarily large, all the available stock is fished, and the expected catch is equal to the expected value of the stock (1).

The other reason why the stable effort strategy is more profitable than the stable catch strategy is that the latter is more costly. For high values of w, the expected catch resulting from optimum stable effort is less than the minimum stock, and it would be feasible to stabilize the catch at this level. This is not optimal, however, because a catch stabilized at a given level $\overline{Y}$ requires a greater effort, on average, than the stable effort $\overline{Z}$, which would give an expected catch equal to $\overline{Y}$. This can be demonstrated as follows: Let Z be stable at $\overline{Z}$. The expected catch from this will be $EY = ES[1-\exp(-\overline{Z})]$, which we may write as

$$\overline{Z} = -\ln(1 - EY/ES).$$

The effort needed on the average to take the catch $\overline{Y} = EY(\overline{Z})$ is

$$EZ = -E\ln(1 - \overline{Y}/S).$$

Since $\ln(1-\overline{Y}/S)$ is a convex function of S, $EZ > \overline{Z}$. In general, if $\overline{Z} = G(ES,\overline{Y})$ and $G(\bullet)$ is a convex function of S, $EZ = EG(S;\overline{Y}) > Z = G(ES,\overline{Y})$.

What conditions, however, might tip the scales in favor of stable catch? According to the analysis in the previous section, a concave revenue function will increase the relative profitability of stabilizing the catch. Let the revenue function be

$$R(Y) = Y^a. \tag{14}$$

For $a < 1$, the revenue function will be concave. The profit function and the first order condition for maximum now are

$$E\pi = \int_{0.5}^{1.5} S^a (1-e^{-z})^a dS - wZ$$
$$= (1.5^{1+a} - 0.5^{1+a})(1-e^{-z})^a/(1+a) - wZ \qquad (5')$$

$$dE\pi/dZ = a(1+a)^{-1}(1.5^{1+a} - 0.5^{1+a})(1-e^{-z})^{a-1}e^{-z} - w = 0 \qquad (6')$$

$$E\pi = Y^a + w\{1.5\ln(1-Y/1.5) - 0.5\ln(1-Y/0.5)$$
$$+Y[\ln(0.5-Y) - \ln(1.5-Y)]\} \qquad (10')$$

$$dE\pi/dY = aY^{a-1} + w[\ln(0.5-Y) - \ln(1.5-Y)] = 0. \qquad (11')$$

Figure 4 shows the maximum profit as a function of the unit cost of effort for stable effort and stable catch, respectively, for $a = 0.5$. For a low unit cost of effort, the effect of being able to take larger catches on the average with stable effort still dominates, and stable effort still yields a higher profit than stable catch. However, the profit of stable effort falls rapidly as the unit cost of effort increases, and the stable catch is seen to yield a higher profit than stable effort over a wide range of the unit cost of effort. Finally, let us look at the case of a rising unit cost of effort. According to the previous section, this should make the stable effort still more attractive. Let the cost of effort function be specified as

$$C(Z) = be^z. \qquad (15)$$

Inserting this into the profit function and the first order condition for maximum profit, we get

$$E\pi = (1-e^{-z}) - be^z \qquad (5'')$$

$$dE\pi/dZ = e^{-z} - be^z. \qquad (6'')$$

By (9), for stable catch, we have $Z = -\ln(1-Y/S)$, so (10) and (11) become

$$E\pi = Y - b\int_{0.5}^{1.5}\exp[-\ln(1-Y/S)]dS$$
$$= Y - b\{1 + Y[\ln(1.5-Y) - \ln(0.5-Y)]\} \qquad (10'')$$

and

$$dE\pi/dY = 1 - b\{(\ln(1.5-Y) - \ln(0.5-Y)$$
$$+Y[(0.5-Y)^{-1} - (1.5-Y)^{-1}]\}. \qquad (11'')$$

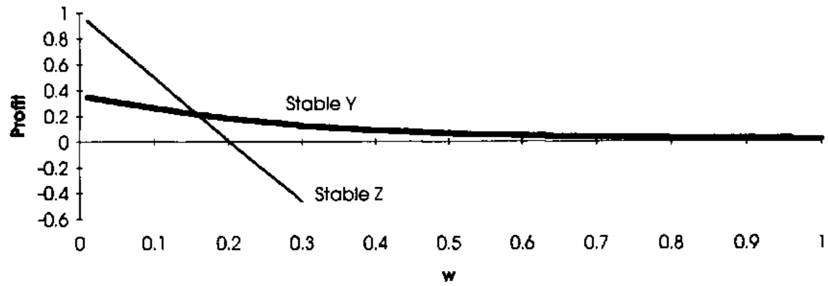

Figure 4. Maximum profit as a function of the unit cost of effort for stable effort and stable catch.

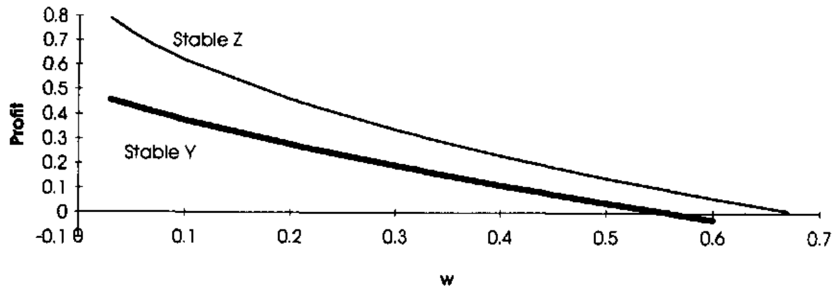

Figure 5. Maximum profit for stable effort and stable catch with a rising unit cost of effort (w is unit cost at Z = 1).

Figure 5 shows the expected profit or optimum stable catch and effort, respectively, as functions of the unit cost of effort at $Z = 1$ (i.e., be^1). As predicted, the stable effort strategy now is even more attractive than in the case with a constant unit cost (cf. Figure 1).

From the analysis of this section, we may conclude there is reason to expect that a stable catch will be less profitable than stable effort, unless the revenue function is concave.

Quasi-Empirical Studies of Two Atlantic Cod Stocks

What might the two stabilization strategies look like in a real world fishery? To answer this question, we simulated the fisheries for two stocks of Atlantic cod,

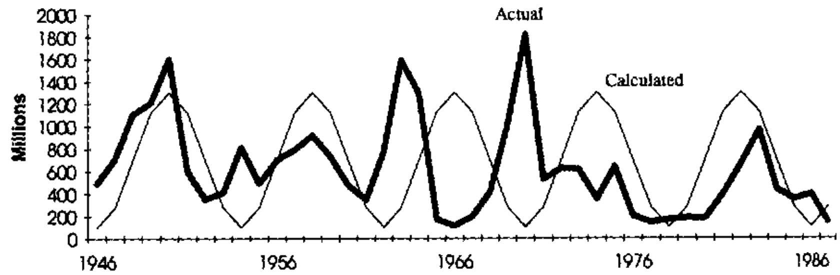

Figure 6. Actual recruitment to both the Arcto-Norwegian cod and Icelandic cod stocks.

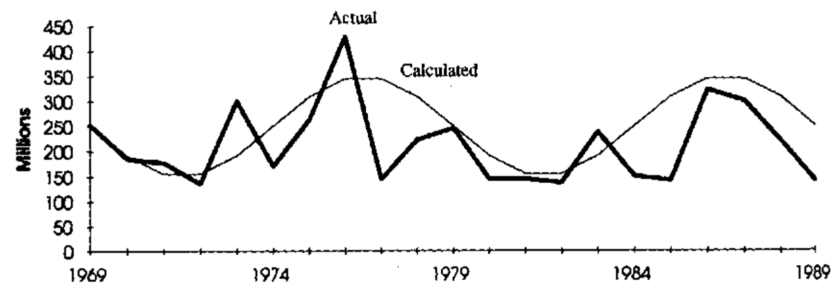

Figure 7. Recruitment produced by a regular cycle (8 years for Arctic cod and 10 years for Icelandic cod).

the Arcto-Norwegian cod and the Icelandic cod. In this section, we summarize the results of this exercise. Both of these have been reported elsewhere (Hannesson and Steinshamn 1991; Hannesson 1989).

Both of these stocks fluctuate considerably over time, largely due to variations in the annual recruitment to the stocks. For the Arcto-Norwegian stock, the recruitment appears to be cyclical, with a periodicity of about 8 years (see Hannesson and Steinshamn 1991). In the simulations to follow, we let the recruitment to both stocks follow a sine curve that produces a regular recruitment cycle. Figures 6 and 7 show the actual recruitment to both stocks and the recruitment produced by a regular cycle (8 years for Arctic cod and 10 years for the Icelandic cod). This cyclical pattern is a simple but not unreasonable way to reproduce realistic fluctuations in the stocks in order to assess the stabilization strategies discussed above.

Table 1. Weight at age parameters (kg).

Age (years)	Iceland	Arcto-Norwegian
3	1.288	–
4	1.725	1.00
5	2.596	1.55
6	3.581	2.35
7	4.371	3.45
8	5.798	4.70
9	7.456	6.17
10	9.851	7.70
11	11.052	9.25
12	14.338	10.85
13	15.273	12.50
14	16.660	13.90
15+	16.660	15.0

Sources: International Council for the Exploration of the Sea, Copenhagen, Arctic Working Group, 1988; and Hafrannsóknastofnun, State of Marine Stocks and Environmental Conditions in Icelandic Waters 1988, Reykjavík, 1988.

The development of the stocks over time was assumed to follow the well-known Beverton-Holt equation, with a constant natural mortality of 0.2. The weight-at-age parameters are shown in Table 1. With a linear relationship between fishing effort and fishing mortality (F) we get

$$F = qZ. \tag{16}$$

In this case, stabilization of effort amounts to the same thing as stabilizing fishing mortality. Nothing is lost in generality by setting $q = 1$. The catch equation we get, instead of (4), then is[4]

$$Y = ZS[1 - \exp(Z + M)]/(Z + M) \tag{17}$$

where M is natural mortality, assumed zero in equation (4).

[4] The catch rate is ZS, while the stock evolves according to the equation $S_t = S_0\exp[-(Z+M)t]$. Integrating the catch equation over one period ($t = 1$) over which the stock is not replenished gives equation (17).

The optimum stable catch and effort, respectively, are found as in the previous section by maximizing the average profit over one recruitment cycle. For expected profit, we substitute average profit, since the fishery model we are using is completely deterministic. The qualitative results derived above are nevertheless valid; we need to substitute only the frequency distribution of the stock size for the probability distribution discussed previously.

Since cod is a long-lived species, the development of the stock over one recruitment cycle is partly determined by the age composition of the stock at the beginning of the period to be investigated. We assume that the stabilization strategy under investigation has been followed for a long time, so that the stock fluctuations have settled down to a stationary pattern. For the stable effort strategy, this means that the initial stock composition can be found by subjecting the year-classes in the stock to a constant fishing mortality over their life history. For the stable catch strategy, the annual fishing mortality will vary inversely with the stock. In this case, the initial age composition of the stock was determined by subjecting the year-classes to the same pattern of fishing mortality as produced by the optimum stable catch over one recruitment cycle.

Let us look, then, at the results produced by the two stabilization strategies for the case of a constant price of fish and unit cost of effort. Tables 2-5 show this for two different cost levels. The first thing to note is that both strategies yield almost the same profit. The stable effort strategy yields, at most, a 2% higher profit for the Arcto-Norwegian cod and less than a 1% higher profit for the Icelandic cod. For both stocks, exploitation is moderate enough that we come nowhere near fishing out either stock when it is at its lowest level; the highest F-values are 0.26 and 0.18, respectively. The stable effort therefore does not result in a much larger average catch than the stable catch, as it did in the examples discussed in the previous section.

One possible argument against stabilizing the catch is that the fishing mortality has to be varied inversely with the stock in order to maintain a stable catch. This potentially is a very risky strategy. If the rate of exploitation necessary to maintain a stable catch in years with a small stock is very high, it might deplete the spawning stock to a dangerously low level. The numbers in Tables 2-5 show that the minimum spawning stock is quite similar under both strategies. This is because the rate of exploitation is very moderate in both strategies, so that a relatively large number of fish reach maturity age. Below we will show examples where the outcome results in significantly smaller spawning stock biomass.

What, then, could make stabilization of the catch more attractive? Above we identified a concave revenue function as one reason why a stable catch would be better than stable effort. Let the price of fish be constant up to the level implied by an optimum stable catch, and zero for any additional catch beyond that level. This produces a kinked revenue function, with the breaking point at

Table 2. Arcto-Norwegian cod. Constant price of fish ($P = 1$) and cost per unit of F ($w = 5{,}000$).

h	4	5	6	7	8	9
			Stable effort			
F	0.075	0.082	0.088	0.093	0.096	0.096
π	413.1	426.9	430.8	419.7	389.0	341.3
EY	788.1	836.9	870.8	884.7	869.0	821.3
Y_{max}	838.1	912.6	971.0	1004.7	1005.1	968.8
Y_{min}	738.1	761.2	770.7	764.8	732.9	673.8
S_{min}	7,290	7,420	7,710	8,161	8,818	9,583
			Stable catch			
Q	790	840	870	880	860	810
π	413.3	426.6	430.0	417.0	384.2	334.5
EF	0.075	0.083	0.088	0.093	0.095	0.095
F_{max}	0.080	0.090	0.099	0.107	0.112	0.114
F_{min}	0.070	0.075	0.078	0.081	0.081	0.079
S_{min}	7,262	7,330	7,635	8,142	8,946	9,841

Table 3. Icelandic cod. Constant price of fish ($P = 1$) and cost per unit of F ($w = 2{,}000$).

h	3	4	5	6	7	8
			Stable effort			
F	0.072	0.076	0.081	0.084	0.085	0.086
π	150.1	150.4	149.3	142.3	130.4	117.6
EY	294.0	302.4	311.3	310.3	300.4	289.6
Y_{max}	305.4	316.2	328.4	325.1	326.0	318.9
Y_{min}	282.7	288.5	294.2	289.2	274.9	260.3
S_{min}	2,974	3,093	3,221	3,430	3,712	3,981
			Stable catch			
Q	294	303	312	310	300	289
π	150.0	150.4	149.2	142.1	130.0	116.8
EF	0.072	0.076	0.081	0.084	0.085	0.086
F_{max}	0.075	0.080	0.085	0.090	0.092	0.095
F_{min}	0.069	0.072	0.076	0.078	0.077	0.077
S_{min}	2,988	3,098	3,190	3,418	3,723	4,018

h = age at first capture (knife-edge selectivity); F = optimum fishing mortality; p = profit; EY = average catch per year; Y_{max} = maximum catch per year; Y_{min} = minimum catch per year; S_{min} = minimum spawning stock (8^+ for Arcto-Norwegian cod, 7^+ for Icelandic cod); Q = optimum stable catch; EF = average fishing mortality; F_{max} = maximum F, F_{min} = minimum F.

Table 4. Arcto-Norwegian cod. Constant price of fish ($P = 1$) and cost per unit of F ($w = 2{,}000$).

h	4	5	6	7	8	9
			Stable effort			
F	0.123	0.138	0.156	0.174	0.190	0.202
π	700.4	745.4	781.9	801.3	793.0	758.4
EY	946.4	1,021.4	1,093.9	1,149.3	1,173.0	1,162.4
Y_{max}	1029.0	1,146.8	1,266.1	1,375.3	1,452.8	1,482.0
Y_{min}	863.8	896.0	921.7	923.2	893.3	842.7
S_{min}	4,709	4,738	4,828	5,113	5,677	6,475
			Stable catch			
Q	950	1,030	1,100	1,150	1,160	1,150
π	701.8	746.6	781.8	798.7	786.4	746.7
EF	0.124	0.142	0.159	0.176	0.187	0.202
F_{max}	0.135	0.161	0.188	0.216	0.237	0.264
F_{min}	0.114	0.125	0.134	0.143	0.146	0.152
S_{min}	4,626	4,535	4,690	5,088	6,046	6,977

Table 5. Icelandic cod. Constant price of fish ($P = 1$) and cost per unit of F ($w = 1{,}000$).

h	3	4	5	6	7	8
			Stable effort			
F	0.109	0.119	0.130	0.141	0.147	0.157
π	238.6	245.8	252.2	250.9	242.9	234.5
EY	347.6	364.8	382.2	391.9	389.9	391.5
Y_{max}	365.8	387.7	410.9	427.5	432.4	443.5
Y_{min}	329.4	341.8	353.5	356.3	347.2	339.5
S_{min}	2,138	2,210	2,320	2,493	2,796	3,061
			Stable catch			
Q	348	365	383	391	390	390
p	238.7	245.9	252.2	250.7	242.3	233.3
EF	0.109	0.119	0.131	0.140	0.148	0.157
F_{max}	0.115	0.127	0.142	0.155	0.166	0.180
F_{min}	0.103	0.112	0.121	0.127	0.131	0.136
S_{min}	2,117	2,178	2,270	2,474	2,801	3,124

h = age at first capture (knife-edge selectivity); F = optimum fishing mortality; p = profit; EY = average catch per year; Y_{max} = maximum catch per year; Y_{min} = minimum catch per year; S_{min} = minimum spawning stock (8^+ for Arcto-Norwegian cod, 7^+ for Icelandic cod); Q = optimum stable catch; EF = average fishing mortality; F_{max} = maximum F; F_{min} = minimum F.

Table 6. Arcto-Norwegian cod. Kinked revenue curve ($R = Y$ for $Y < Q$, $R = Q$ for $Y > Q$). Constant cost per unit of F ($w = 5{,}000$).

h	4	5	6	7	8	9
			Stable effort			
F	0.067	0.072	0.074	0.075	0.076	0.074
π	410.0	421.8	422.5	408.7	376.4	329.0
EY	745.0	782.9	793.5	783.9	757.5	699.1
Y_{max}	789.5	849.6	878.2	881.2	864.4	811.3
Y_{min}	700.5	716.3	708.8	686.5	712.7	586.9
S_{min}	7,855	8,056	8,532	9,130	9,790	10,539
			Stable catch			
Q	790	840	870	880	860	810
π	413.3	426.6	430.0	417.0	384.2	334.5
EF	0.075	0.083	0.088	0.093	0.095	0.095
F_{max}	0.080	0.090	0.099	0.107	0.112	0.114
F_{min}	0.070	0.075	0.078	0.081	0.081	0.079
S_{min}	7,262	7,330	7,635	8,142	8,946	9,841

Table 7. Icelandic cod. Kinked revenue curve ($R = Y$ for $Y < Q$, $R = Q$ for $Y > Q$). Constant cost per unit of F ($w = 2{,}000$).

h	3	4	5	6	7	8
			Stable effort			
F	0.067	0.070	0.074	0.075	0.075	0.074
π	149.5	149.7	148.5	141.2	129.0	115.9
EY	283.5	289.7	296.5	291.2	279.1	263.9
Y_{max}	294.1	302.3	312.0	310.0	301.8	289.5
Y_{min}	283.2	277.1	281.1	272.4	256.5	238.4
S_{min}	3,114	3,249	3,385	3,633	3,905	4,189
			Stable catch			
Q	294	303	312	310	300	289
π	150.0	150.4	149.2	142.1	130.0	116.8
EF	0.072	0.076	0.081	0.084	0.085	0.086
F_{max}	0.075	0.080	0.085	0.090	0.092	0.095
F_{min}	0.069	0.072	0.076	0.078	0.077	0.077
S_{min}	2,988	3,098	3,190	3,418	3,723	4,018

h = age at first capture (knife-edge selectivity); F = optimum fishing mortality; p = profit; EY = average catch per year; Y_{max} = maximum catch per year; Y_{min} = minimum catch per year; S_{min} = minimum spawning stock (8^+ for Arcto-Norwegian cod, 7^+ for Icelandic cod); Q = optimum stable catch; EF = average fishing mortality; F_{max} = maximum F; F_{min} = minimum F.

Table 8. Arcto-Norwegian cod. Kinked revenue curve ($R = Y$ for $Y < Q$, $R = Q$ for $Y > Q$). Costless F ($w = 0$).

h	4	5	6	7	8	9
			Stable effort			
F	0.176	0.200	0.228	0.262	0.323	0.380
π	973.9	1,047.0	1,118.1	1,179.9	1,221.9	1,227.5
EY	1,005.9	1,095.9	1,184.3	1,261.9	1,328.5	1,360.9
Y_{max}	1,123.8	1,272.4	1,432.3	1,606.9	1,797.8	1,931.3
Y_{min}	887.9	919.4	936.3	917.0	859.2	790.7
S_{min}	2,983	2,987	3,076	3,273	3,416	3,878
			Stable catch			
Q	1,018	1,118	1,224	1,325	1,422	1,464
π	1,018	1,118	1,224	1,325	1,422	1,464
EF	0.209	0.255	0.351	3.973	4.530	4.259
F_{max}	0.240	0.315	0.487	22.855	26.728	26.772
F_{min}	0.181	0.206	0.252	0.422	0.408	0.391
S_{min}	2,227	1,936	1,433	0	1,433	2,953

Table 9. Icelandic cod. Kinked revenue curve ($R = Y$ for $Y < Q$, $R = Q$ for $Y > Q$). Costless F ($w = 0$).

h	3	4	5	6	7	8
			Stable effort			
F	0.191	0.215	0.253	0.293	0.337	0.433
π	376.1	397.3	423.3	439.4	446.1	464.3
EY	386.0	410.4	439.7	459.9	471.5	495.2
Y_{max}	419.7	454.9	500.1	535.8	563.3	611.3
Y_{min}	352.4	365.8	379.3	384.0	379.8	379.0
S_{min}	1,088	1,084	1,121	1,231	1,456	1,579
			Stable catch			
Q	388	414	446	469	480	509
π	388	414	446	469	480	509
EF	0.207	0.249	0.323	0.431	0.480	3.184
F_{max}	0.228	0.284	0.387	0.555	0.645	18.900
F_{min}	0.187	0.218	0.269	0.334	0.356	0.623
S_{min}	928	851	735	697	1,102	1,005

h = age at first capture (knife-edge selectivity); F = optimum fishing mortality; p = profit; EY = average catch per year; Y_{max} = maximum catch per year; Y_{min} = minimum catch per year; S_{min} = minimum spawning stock (8+ for Arcto-Norwegian cod, 7+ for Icelandic cod); Q = optimum stable catch; EF = average fishing mortality; F_{max} = maximum F; F_{min} = minimum F.

the level of the optimum stable catch. Tables 6-9 show results obtained for a high cost and a zero cost per unit of fishing effort. The results obtained for the high cost case show that stable catch now is the more profitable strategy, but the difference still is small or about the same in percentage terms as in Tables 2-5.

For the zero cost case, the result is more dramatic. The difference in profitability now is up to 10% (Icelandic cod) and 20% (Arcto-Norwegian cod) in favor of the stable catch strategy. More significantly, the smallest spawning stock now is considerably lower in the stable catch strategy; in one case for the Arcto-Norwegian cod, it is wiped out entirely. The optimum stable catch now is high enough that the available stock in some cases is virtually wiped out when it is at its lowest, as indicated by the very high values of fishing mortality in Tables 8 and 9. Needless to say, such harvesting would hardly be optimal for a stock that must reproduce and be utilized on a sustained basis; this last example serves to underline the riskiness of stabilizing the catch at a high level that otherwise would be desirable when the costs of fishing are low or negligible.

The zero cost case also may serve to show the difference between stabilizing the catch and stabilizing fishing mortality, for the situation where the catch per unit of effort is constant and independent of the stock. Stabilizing effort then amounts to the same thing as stabilizing the catch, due to the proportionality between catch and effort. Because of this, and given that the cost per unit of fish caught is constant, the cost of fishing can be accounted for directly in the price of fish, evaluating the catch at a price net of the unit cost of fishing to find the profit of any given catch.

Conclusion

Plausible arguments for stabilizing both the catch of fish and the activity of the fishing fleet (effort) are not difficult to find. Unfortunately, stabilizing one is likely to destabilize the other. Economic circumstances sometimes will favor one of these and sometimes the other, while biological and technological constraints seem most likely to favor stable effort.

The difference in profitability between stable catch and stable effort appears to be surprisingly small for multi-year class stocks. Stabilization of the catch, as advocated by the processing industry, does not appear to yield very great benefits, even if the marginal benefit of catch diminishes as the catch increases. Disadvantages of catch fluctuations on the marketing and processing side would give rise to, or can be modeled as, an ex-vessel price of fish which falls with increases in landings.

The model generating the fluctuations in the two cod stocks under consideration is highly stylized, but goes a long way toward capturing what appears to be wave-like dynamics of the stocks. The reason for using the sine-function approach is simplicity. It is not entirely clear, however, what factors a more realistic model of the recruitment process might incorporate. One possibility is a sine-function, or some other periodic function, with a random element. Early precursors to this work using random recruitment showed results that were not qualitatively different from those reported here. Another possibility is that deterministic dynamics of the stock itself (a spawning stock-recruitment relation together with cannibalism) generates the fluctuations. The optimum exploitation of such a system is likely to be different from this and to imply stabilization of the stock at some level, but an analysis of that problem would be a subject worthy of another paper.

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