The dynamics of an open access fishery

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Abstract. A discrete time non-linear deterministic model for an open access fishery is developed and the equilibrium is characterized. The open access exploitation of North Sea herring during the period 1963–77 is analysed. Alternative production functions are considered and estimated for the Norwegian purse seine fishery. The bionomic equilibrium and approach dynamics are presented when prices and costs are changing. The results indicate that the resource stock was saved from possible extinction by the closure of the fishery at the end of the 1977 season.

Sur la dynamique d'une zone de pêches quand l'entrée est libre. Les auteurs développent un modèle déterministe non-linéaire en temps discret d'une zone de pêches où l'entrée est libre et définissent les caractéristiques de l'équilibre. L'exploitation du hareng de la Mer du Nord qui s'est faite sans entraves à l'entrée pendant la période 1963–1977 est analysée avec ce modèle. Des fonctions de production de rechange sont examinées et calibrées pour la pêche à l'essaugue par la flotte norvégienne. L'équilibre bionomique et la dynamique de l'approche à cet équilibre sont examinés dans un univers où les prix et les coûts sont changeants. Les résultats de l'analyse montrent que le stock de ressource a échappé à la disparition possible grâce à la fermeture de la zone de pêches à la fin de la saison de 1977.

INTRODUCTION

Open access exploitation of common property fish resources frequently causes severe stock depletion. Indeed, the question whether open access may cause stock extinction has been analysed by several authors (Smith, 1968 and 1975; Berck, 1979; Hartwick, 1982). Moreover, as Smith (1968) has pointed out, although stock equilibrium under open access may be positive, the stock may be driven to extinction along the path of adjustment. Stock equilibrium may also be stable and positive with fixed prices and technology and still drift towards extinction over time, since these fixed variables drift in the long run.

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With the exception of Wilen (1976) the work on the dynamics of open access or free entry fisheries is mainly theoretical. The purpose of this paper is to provide an empirical application, based on the North Sea herring fishery, with special reference to the question of stock extinction under open access. Herring is a schooling species. The schooling behaviour has permitted the development of very effective harvesting techniques. With modern fish-finding equipment, harvesting can remain profitable even at low stock levels. Open access exploitation of a number of schooling species has caused severe stock depletion (Murphy, 1977). The question of possible stock extinction thus takes on special importance for schooling species.

In the second section we shall develop a deterministic model for an open access fishery based on Smith (1968) and give a characterization of open access equilibrium. In the following section open access exploitation of North Sea herring during the period 1963–77 will be analysed. Alternative production functions are considered and estimated for the Norwegian purse seine fishery. The bionomic equilibrium and approach dynamics are presented when prices and costs are changing. Finally, the work is summarized and some policy implications are discussed.

THE OPEN ACCESS MODEL

In this section we construct a simple open access model to discuss steady state (equilibrium) conditions and system dynamics. The model will be specified in discrete time as a system of difference equations. Time is partitioned into annual increments, a procedure consistent with the data used to estimate production and growth functions and the equation for capital (vessel) dynamics. It is also consistent with the observation that vessel owners are reluctant to incur the cost of regearing once a decision has been made to enter the herring fishery which, in the North Sea, has a season running from May until September. While the steady state equilibria for differential equation systems and their difference-equation analogues are usually equivalent, the stability and thus approach dynamics can be qualitatively different. The distinction becomes more than a mathematical curiosity in resource systems, where discrete-time and possibly lagged adjustment to biological and economic conditions can lead to overshoot and greater potential for overharvest and possibly species extinction.

The model presumes an industry production function

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

where Y_t is yield (harvest) in year t, K_t are the number of vessels in the fishery during year t, and S_t is the fishable stock at the beginning of year t.

The number of vessels, K_t, may be a crude measure of actual fishing effort. In demersal fisheries the best measure might be the volume of water 'screened' by nets during the season (Clark, 1985). However, in a fishery on a schooling species like herring, search for schools of herring is of predominant importance. Accordingly, in such fisheries the number of participating vessels may be an appropriate measure of effort.

For schooling stocks, like herring, there is some question as to 'elasticity' of yield with respect to stock size, S_t. If as a population declines it continues to concentrate in (fewer) schools of the same approximate size, and if these schools can be located with relative ease by electronic search, then yield may be essentially determined by effort, independent of stock, until the population declines to a small number of schools. If this were the case, the production function $H(\cdot)$ might depend strictly on K_t, and catch per unit effort, often used to estimate stock, would not predict the collapse of the fishery (Clark and Mangel, 1979; Ulltang, 1980).

Assuming that vessel numbers are an appropriate measure of effort and that yield is stock dependent, the standard open access model proceeds by defining industry profit (net revenue) in year t as

$$\pi_t = pH(\cdot) - cK_t, \tag{2}$$

where p and c are the per unit price for yield and cost per vessel, respectively. Two additional assumptions are implicit in equation (2). First, the fishery must be one of several sources of the species in question; otherwise price would depend on yield, that is, $p_t = p(Y_t)$ where $p(\cdot)$ is an inverse demand function. Cost per vessel is also assumed given. Second, the unit prices and costs are assumed constant through time. Neither assumption is likely to hold in 'real world' fisheries, but their maintenance permits the estimation of an open access or bionomic equilibrium, which may give an indication of the extent of overfishing.

Vessels are assumed to enter a profitable fishery and exit an unprofitable fishery according to

$$K_{t+1} - K_t = n\pi_t \tag{3}$$

where $n > 0$ is an adjustment parameter (unit: vessels/\$). With n positive, it will be the case that (a) $K_{t+1} > K_t$ if $\pi_t > 0$; (b) $K_{t+1} < K_t$ if $\pi_t < 0$; and (c) $K_{t+1} = K_t$ if $\pi_t = 0$. It is possible that the rates of entry and exit may differ, in which case n^+ might apply if $\pi_t > 0$ and n^- might apply if $\pi_t < 0$ where $n^+, n^- > 0$, $n^+ \neq n^-$.

Finally, the resource stock is assumed to adjust according to

$$S_{t+1} - S_t = F(S_t) - H(K_t, S_t), \tag{4}$$

where $F(S_t)$ is a net natural growth function. It is often assumed that there exist stock levels $\mathbf{S}$ and $\bar{S}$ where $F(\mathbf{S}) = F(\bar{S}) = 0$, $F(S) < 0$ for $0 < S < \mathbf{S}$, $F(S) > 0$ for $\mathbf{S} < S < \bar{S}$, and $F(S) < 0$ for $S > \bar{S}$.

Taken together equations (3) and (4) constitute a dynamical system (or an iterative map). More specifically, with given values for S_0 and K_0 the system

$$\begin{aligned} K_{t+1} &= K_t + n[pH(K_t,S_t) - cK_t] \\ S_{t+1} &= S_t + F(S_t) - H(K_t, S_t) \end{aligned} \tag{5}$$

can be iterated forward in time. The trajectory (S_t, K_t) may be plotted in phase-space. A stationary point (S, K) is one for which $K_{t+1} = K_t = K$ and $S_{t+1} = S_t = S$ for all future t. Such a point must satisfy $K = pH(K, S)/c$ and $H(K, S) = F(S)$.

For the Gordon-Schaefer model (Clark, 1976) where $F(S_t) = rS_t(1 - S_t/L)$ and $H(K_t, S_t) = qK_tS_t$, the differential equation system takes the form

$$\begin{aligned} \dot{K} &= n(pqKS - cK) \\ \dot{S} &= rS(1 - S/L) - qKS, \end{aligned} \tag{6}$$

where r is the intrinsic growth rate, L is the environmental carrying capacity, and q is the catchability coefficient. The system has an equilibrium at $S_\infty = c/(pq)$ and $K_\infty = r(1 - S_\infty/L)/q$, which is the focus of a stable spiral (see figure 1a). The difference equation analogue might be written

$$\begin{aligned} K_{t+1} &= [1 + n(pqS_t - c)]K_t \\ S_{t+1} &= [1 + r(1 - S_t/L) - qK_t]S_t, \end{aligned} \tag{7}$$

and is capable of more complex behaviour, including limit cycles (see figure 1b).[1]

THE NORTH SEA HERRING FISHERY 1963–77

The North Sea herring fishery takes place in the central and northern North Sea, with the main season in the months May to September. In the present case study data for the Norwegian purse seine fleet will be used to estimate production functions and vessel dynamics. The fishery, utilizing this technology, started in 1963. In the middle of the 1970s, however, the stock was severely depleted under an open access regime and the fishery was closed at the end of 1977. Severe regulations have been in effect ever since to allow the stock to recover.

Table 1 contains data on stock size, Norwegian purse seine harvest and the number of Norwegian purse seiners for the period 1963–77. Other countries (Denmark, the Netherlands, Germany, and the United Kingdom) were also harvesting the herring stock using a variety of gear, including single and pair

1 For system (6) with $S_\infty = c/(pq) > 0$ and $K_\infty = r(1 - S_\infty/L)/q > 0$ the open access equilibrium is stable (a node or spiral) and limit cycles are precluded by the Bendixon-du Lac test (see Clark, 1976, 203–4). For the difference equations in system (7), simulation for $p = 1{,}000$, $c = 3{,}000$, $q = 3.8 \times 10^{-5}$, $n = 0.0001$, $r = 0.5$, and $L = 250{,}000$ from $S_0 = 250{,}000$ and $K_0 = 1{,}000$, results in a convergent spiral. Changing n to 0.000175 leads to a limit cycle and with $n = 0.000175$ and $r = 2.6$, ceteris paribus, an invariant circle is obtained. The difference equation system, with its inherent lag, is capable of much more complex, possibly 'chaotic' behaviour.

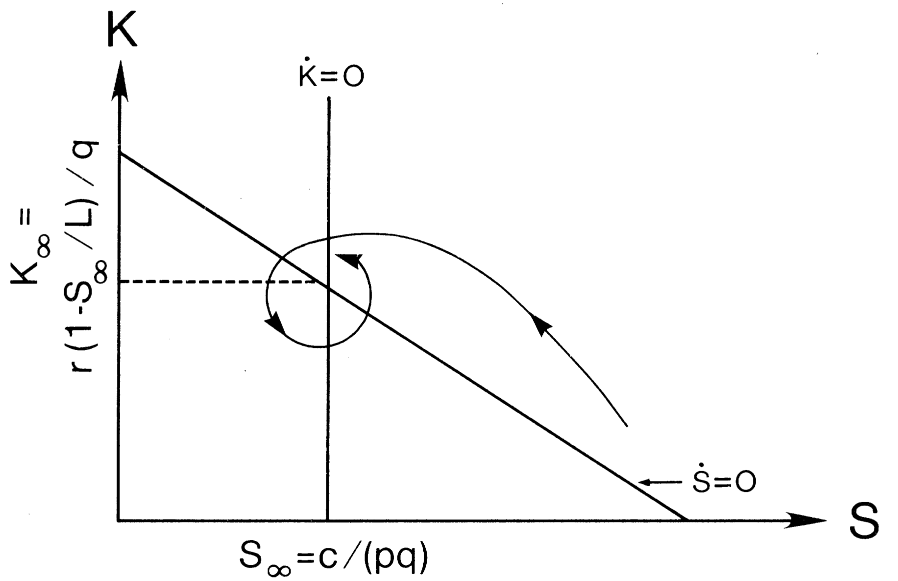

FIGURE 1a: Phase plane analysis of system (6). The point (S_∞, K_∞) is the focus of a stable spiral.

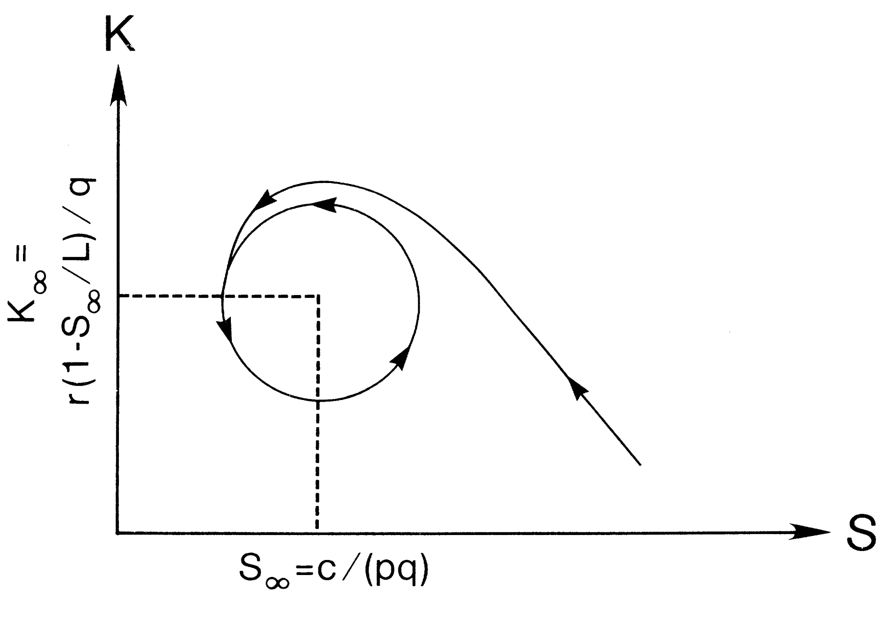

FIGURE 1b: Phase plane analysis of system (7). The point (S_∞, K_∞) is the focus of a limit cycle.

TABLE 1

North Sea herring stock, Norwegian purse seine harvest, and the number of Norwegian purse seiners

Year	Stock size S_t (tonnes)	Norwegian harvest Y_t (tonnes)	Number of participating purse seiners K_t
1963	2,325,000	3,454	8
1964	2,529,000	147,933	121
1965	2,348,000	586,318	209
1966	1,871,000	448,511	298
1967	1,434,000	334,449	319
1968	1,056,000	286,198	352
1969	696,000	134,886	253
1970	717,000	220,854	201
1971	501,000	210,733	230
1972	509,000	136,969	203
1973	521,000	135,338	153
1974	345,000	66,236	165
1975	259,000	34,221	102
1976	276,000	33,057	92
1977	166,000	3,911	24

SOURCE: Bjørndal (1984)

trawl and drift nets. After 1963, however, the purse seine technology became the dominant gear, and lacking data on the number and harvest of other gear types, we used the Norwegian purse seine data to estimate parameters for several alternative production forms. The stock estimates (S_t) were obtained by virtual population analysis (Ricker, 1975). Unrestricted OLS regressions were run, and table 2 shows four estimating equations (a)(i)–(d)(i) and four associated production functions (a)(ii)–(d)(ii). The exponents on K_t in (a)(ii) and (b)(ii) would indicate a yield/vessel elasticity greater than one. This is presumably the result of economies of scale in searching for schools of herring, since information about locations of schools tends to be shared between boats in this fishery. The yield-stock elasticity in (b)(ii) and (d)(ii) are both significantly positive and less than one. Thus, as stock declines, catch per vessel will decline and there will be a stock-dependent incentive to exit from the industry, as indicated by the rather rapid departure of Norwegian purse seiners from the fishery after 1968. The remaining vessels, however, seemed more than adequate to continue harvest in excess of natural growth and recruitment, and from inspection of table 1 it is still not clear whether exit would have been rapid enough for the stock to increase.

The expression for profits was specified as

$$\pi_t = p_t H(K_t, S_t) - c_t K_t, \tag{8}$$

where $c_t = e_t \tilde{c}_t + f_t$; e_t is the average number of days spent fishing herring, $\tilde{c}_t$ is the operating cost per day in year t, and f_t are the fixed and opportunity costs incurred during the herring season.

TABLE 2

Estimates of production function parameters for the Norwegian purse seine fleet; all regressions OLS with t-statistics in parentheses[a]

(a)(i) $\ln Y_t = \underset{(5.86)}{4.5408} + \underset{(9.11)}{1.4099} \ln K_t$ (adjusted $R^2 = 0.85$)

(ii) $Y_t = 93.769\, K_t^{1.41}$

(b)(i) $\ln Y_t = \underset{(2.11)}{-2.7876} + \underset{(16.39)}{1.3556} \ln K_t + \underset{(5.84)}{0.5621} \ln S_t$ (adjusted $R^2 = 0.96$)

(ii) $Y_t = 0.06157\, K_t^{1.356} S_t^{0.562}$

(c)(i) $\ln (S_t - Y_t) = \underset{(1.29)}{-0.5683^b} + \underset{(30.81)}{1.0398^c} \ln S_t - \underset{(3.74)}{0.0011} K_t$ (adjusted $R^2 = 0.99$)

(ii) $Y_t = S_t(1 - e^{-0.0011K_t})$

(d)(i) $\ln (Y_t/K_t) = \underset{(0.84)}{-1.6718^b} + \underset{(4.16)}{0.6086} \ln S_t$ (adjusted $R^2 = 0.54$)

(ii) $Y_t = S_t^{0.609} K_t$

[a] Autocorrelation was indicated only in equations (a) and (d). First-order correction did not significantly alter the magnitude of the estimated coefficients. Two-stage least squares did not indicate the presence of simultaneous equations bias which can occur if estimates of S_t are based on current period harvest. This is less of a problem when stock estimates are obtained by virtual population analysis.

[b] Not significantly different from zero; parameter assumed to be zero in the associated production function.

[c] Not significantly different from 1.00; parameter set equal to one in the associated production function.

Vessel dynamics were assumed to occur according to

$$K_{t+1} - K_t = n\pi_t/(p_t K_t). \tag{9}$$

Equation (9) assumes that entry or exit will depend on the sign of normalized profit per boat. This form was employed to take advantage of previous analysis by Bjørndal and Conrad (1985). Estimates of n ranged between 0.08 and 0.10.

A discrete-time analogue to the logistic growth function might be written as

$$S_{t+1} - S_t = rS_t(1 - S_t/L), \tag{10}$$

where estimates of r and L were 0.8 and 3.2×10^6 metric tonnes. Equation (10) is an approximation to a more complex delay-difference equation discussed in Bjørndal (1984).

Of the four production models the Cobb-Douglas form $Y_t = aK_t^b S_t^g$, resulted in the most plausible values for the bionomic equilibrium and open access dynamics. The open access system may be written as

TABLE 3

Costs (per season per vessel) and herring price (per tonne); figures in Norwegian kroner[a]

Year	c_t	p_t
1963	190,380	232
1964	195,840	203
1965	198,760	205
1966	201,060	214
1967	204,880	141
1968	206,800	128
1969	215,200	185
1970	277,820	262
1971	382,880	244
1972	455,340	214
1973	565,780	384
1974	686,240	498
1975	556,580	735
1976	721,640	853
1977	857,000	1,415

[a] Price figures have been adjusted by a factor of 0.6, which represents the boat owner's share of income. Costs cover only costs incurred by the boatowner.

SOURCES: p_t: The Directorate of Fisheries, Norway
c_t: The Budget Committee for the Fishing Industry, Norway

$$\begin{aligned} K_{t+1} &= K_t + n(aK_t^{b-1}S_t^g - c_t/p_t) \\ S_{t+1} &= S_t + rS_t(1 - S_t/L) - aK_t^b S_t^g. \end{aligned} \tag{11}$$

If $c_t = c$ and $p_t = p$, then one obtains the following equations for the bionomic equilibrium

$$\begin{aligned} S_\infty &= [c/(paK_\infty{}^{b-1})]^{1/g} \\ K_\infty &= [rS_\infty(1 - S_\infty/L)/(aS_\infty{}^g)]^{1/b} \end{aligned} \tag{12}$$

While it is not possible to solve for explicit expressions for S_∞ and K_∞, it is possible to solve for S_∞ and K_∞ numerically. By making an initial guess for K_∞, the first equation in (12) provides a value for S_∞. Substituting this value into the second equation one obtains a value for K_∞, consistent with growth and yield. Calling the initial guess Z_∞, one can evaluate $|Z_\infty - K_\infty|$. If this is not within an arbitrary ϵ, readjust the guess according to $Z_\infty = (Z_\infty + K_\infty)/2$. This process will converge to the bionomic equilibrium from above or below K_∞.

During the period 1963–77 prices and costs were changing as indicated in table 3. If the 1975 values of $c = 556{,}580$ and $p = 735$ (both in Norwegian kroner) were somehow fixed into the future and all other parameters remained unchanged, then the bionomic equilibrium is calculated at $S_\infty = 430{,}191$ (tonnes), $K_\infty = 393$ (boats), and $Y_\infty = 297{,}887$ (tonnes). When c_t and p_t are allowed to vary as per table 3, the time paths for S_t and K_t are given in table 4

TABLE 4

Bionomic equilibrium and open access dynamics

System

$$K_{t+1} = K_t + n(aK_t^{b-1}S_t^g - c_t/p_t)$$

$$S_{t+1} = S_t + rS_t(1 - S_t/L) - aK_t^b S_t^g.$$

Parameter values

$a = 0.06157$, $b = 1.356$, $c = 556{,}580$, $g = 0.562$

$L = 3{,}200{,}000$, $n = 0.1$, $p = 735$, $r = 0.8$

Bionomic equilibrium

$S_\infty = 430{,}191$, $K_\infty = 393$, $Y_\infty = 297{,}887$

Open access dynamics

With c_t and p_t as given in table 3, $S_0 = 2{,}325{,}000$, $K_0 = 120$, then

Year	S_t	K_t	Y_t
1963	2,325,000	120	153,698
1964	2,679,895	166	258,531
1965	2,769,820	225	398,376
1966	2,669,323	305	588,874
1967	2,434,586	404	818,564
1968	2,081,887	461	897,077
1969	1,766,756	494	898,025
1970	1,501,779	559	970,003
1971	1,169,363	626	983,051
1972	779,950	626	782,754[a]
1973	469,075	538	479,232
1974	310,096	480	325,061
1975	209,071	410	210,287
1976	155,113	385	163,580
1977	109,609	343	115,016

[a] After 1972 harvest exceeds S_t but *not* S_t plus growth. This is possible, since growth to the resource occurs before harvesting (see equation for S_{t+1}, above).

and plotted in phase-space in figure 2. The values for K_t might be interpreted as an estimate of 'purse seine equivalents' fishing herring in the *entire* North Sea. Thus K_t is larger than the number of Norwegian purse seiners that participated in the fishery during the period. The stock actually increases until 1965 and then decreases monotonically. The estimates of the herring stock in table 1 are a bit more ragged, lower than the simulated estimates until 1973 and higher thereafter. Of particular interest is the overshoot 'past' the 1975-based bionomic equilibrium and the continued decline in stock. In contrast to the results of Wilen, there is no increase in the stock and the 'first loop' of a convergent spiral has *not* been completed.

In 1977 Norway and the EEC agreed to close the fishery. There are no official

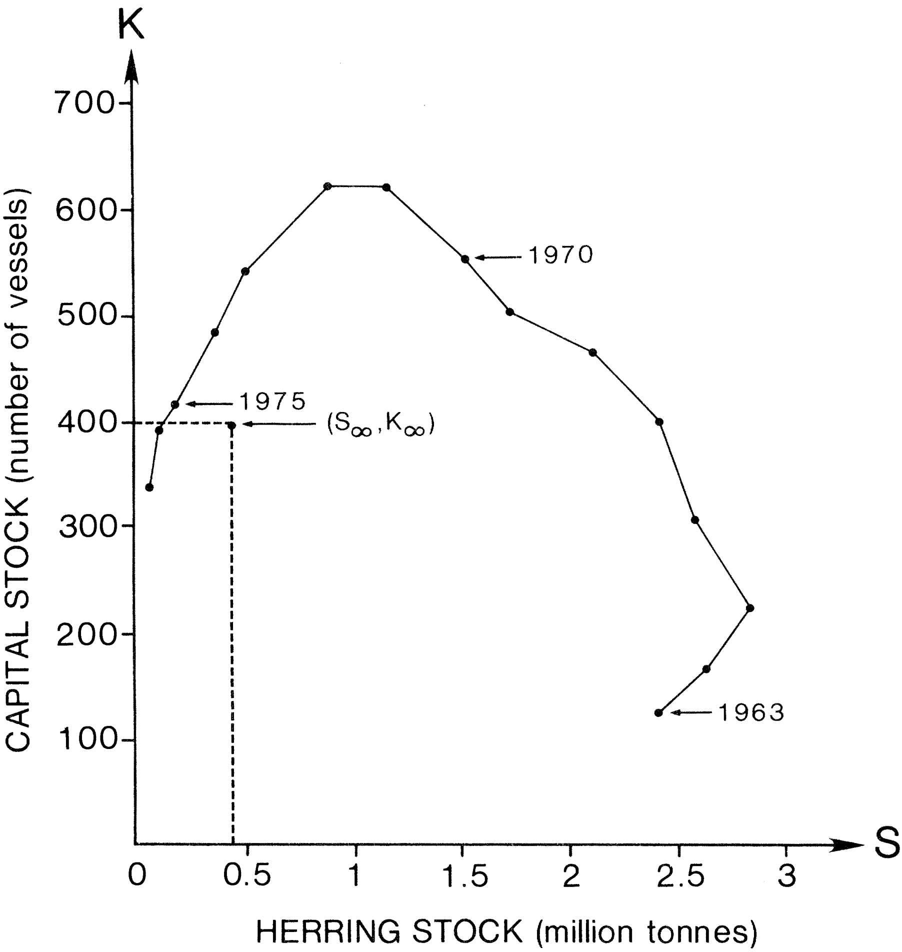

FIGURE 2. Simulation of North Sea herring fishery.

prices nor data to estimate costs after this year. One can only speculate what the future evolution of stock and vessel numbers would have been. It seems entirely plausible that with declining harvest, relative price increases would have exceeded relative cost increases with species extinction the result. If the price in 1978 were increased to 2,000 NoK/metric tonne and costs held steady, the species 'simulates' to extinction in 1983. Under the moratorium which lasted until 1981 the stock was allowed to recover, and fisheries scientists estimated the 1983 stock level at 600,000 metric tonnes.

CONCLUSIONS AND POLICY IMPLICATIONS

In the empirical analysis of open access systems it is important to note that non-linear difference equations, with or without longer lags, are capable of more complex dynamic behaviour than their continuous-time (differential equation) analogues. The lag in adjustment by both the exploited species and the harvesters themselves is often a more accurate depiction of dynamics, and the differential equation systems are best viewed as theoretical approximations.

If adjustment in an open access system is discrete, there is a greater likelihood of overshoot, severe depletion, and possibly extinction. When discrete adjustment takes place in a system where the species exhibits schooling, declining stocks may fail to reduce profits rapidly enough to turn the critical 'first corner' in an approach to bionomic equilibrium. The fact that the economic and natural environments are subject to fluctuations places greater importance on modelling the dynamics of non-autonomous systems as opposed to the calculation of equilibria based on long-run or average values.

The analysis of the North Sea herring fishery would seem to support many of the above points. During the 1963–77 period the resource (1) was subject to open access exploitation by Norway and members of the EEC; (2) exhibited a weak yield-stock elasticity (because of schooling) which failed to encourage a rapid enough exit of vessels from the fishery; and (3) was saved from more severe overfishing and possibly extinction by the closure of the fishery at the end of the 1977 season.

Recent analysis by Bjørndal (1985) indicates that the optimal stock level is likely to be in the range 1.0–1.4 million tonnes, supporting a harvest of 550,000–600,000 tonnes. With the recovery of the resource, the stock might be initially managed through a system of *inter*nationally assigned but *intra*nationally transferable quotas. In the longer run a system allowing fisheries managers from one country to purchase or lease the quota rights of another should permit the total allowable catch (TAC) to be harvested at least cost. The theory and institutions for the management of transboundary resources are still at an early stage of development, but likely to be of critical importance if the value of fisheries resources are to be maximized among coastal countries.

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