Stock variations due to symbiotic behavior - An attempt to understand the fluctuations in the cod fisheries of the Barents Sea

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Abstract. This paper presents a simple two species symbiotic. The model is applied on the cod stock of the Barents Sea, conceiving the mature and immature parts of the stock to represents different species that depends on each other's. The mature part is assumed to predate on the immature, while the recruitment of each part depends on the size of the other. The parameters of the symbiotic model are estimated statistically, using available data for the period 1962-1990. According to the symbiotic model, the cannibalistic behavior of cod can explain most of the observed fluctuations in the stock growth during this period. The dynamics of the model allow cyclic changes in growth pattern, depending on the fishing activity. Constant harvest rates of mature and immature cod will always establish an equilibrium situation (stable focus). To investigate some economic implications of the symbiotic behavior between mature and immature cod, a simple bioeconomic model has been applied. According to this model the economic loss of size selection exceed the gain even when there is no selection costs. When mature and immature cod have the same market value, it will be optimal with a non-selective fishery, while selection will be optimal when the price of mature cod exceeds 105% of the price of immature cod. A maximum economic yield of 0.9 billion NOK is achieved by a non-selective fishery, using available price and cost information.

1. INTRODUCTION

There has been a substantial variation in the cod fisheries and in the stock size of cod in the Barents Sea, over several years. When Johan Hjort wrote his seminal work about the fluctuations in the great fisheries of Northern Europe (Hjort [1914]), these phenomena had been known for a long time. Hjort also provided a historical overview, where he referred to written sources, both from fishermen, scientists and official authorities, back from the beginning of the eighteenth century.

The biomass reduction of the cod stock, from the sixties until today, is often assumed to be closely related to the increased fishing activity during this period. In addition to the negative trend of the biomass, there has also been substantial year to year fluctuations in the size of the cohorts during the period 1962-1990 (Figure 1). Several very poor cohorts followed the rich cohorts of 1963 and 1964; the cohort of 1966 being the poorest ever measured. The same pattern is repeated after the rich cohorts of 1969 and 1970.

Figure 1 shows that even in years when the total biomass of the cod stock exceeded 3 million tons, a substantial part of the biomass was related to one of two cohorts. After 1977/1978 and in the beginning of the eighties, however, this was changed. No strong cohort seems to dominate during this period. With one single exception of the cohort of 1975, no cohorts were stronger than the medium cohorts of the early seventies were.

In principal four reasons can be given to explain the substantial fluctuations we are able to observe in the cod stock:

- *Environmental changes.* (Variations in temperature, salinity, directions of currents, etc.)
- *The dynamics of the ecosystem.* (The multispecies dynamics.)
- *The dynamics of open access fisheries.*
- *The dynamics of the stock.* (The dynamics of recruitment and cannibalism.)

Probably are all these factors as causes of the observed fluctuations. To include all these dynamics in one single model, one has to create a model of such a complexity that it would be of little, if any, practical use. The interesting question then is: How much of the observed fluctuation can be explained by a model including only one of the four reasons? And how useful can such a model be in gaining new understanding of the dynamics behind the fluctuations?

2. DATA

ICES has carried out stock assessments of the Barents Sea cod stock over a long period of time. Estimates based on Virtual Population Analysis (Gulland [1967]) are available from 1962. The technique used depends heavily on the catch data, but some tuning procedures involving other sources of information, have now been added. Generally the nesting procedure of the VPA technique will give less certain estimates for the first years in the calculation, which is the last years.

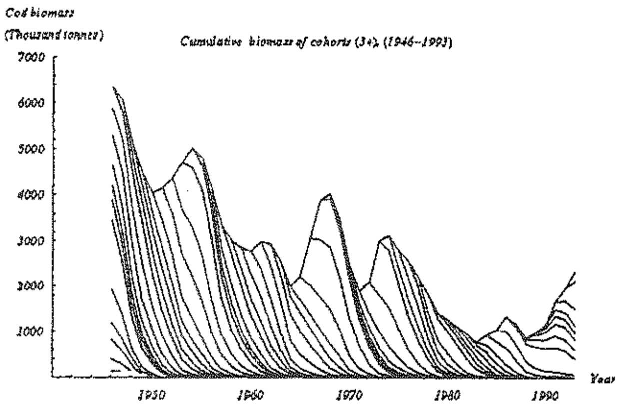

Figure 1. Estimated cod biomass during the period 1946-1993. The graph shows the cumulated biomass of each year-class, the upper line representing the total biomass of the stock. Each year a new year-class is added on the upper line (representing the year-class of last year). The data are from Anon. [1992)].

Table 1. Stock estimates and reported harvest of immature and mature cod in million tons from 1962 to 1990. Number of individuals of each cohort at any age is estimated by VPA (Anon. [1992]). Individual weights at age in stock and in catch, are calculated from data collected on surveys and catch records. Mature fraction of each cohort is also calculated from survey results (Anon. [1992]).

Year	Immature biomass (y)	Mature biomass (x)	Catch of y	Catch of x
1962	2.311	0.8127	0.5637	0.3455
1963	2.0453	0.7083	0.4736	0.3028
1964	1.9464	0.5412	0.2539	0.1838
1965	2.3595	0.603	0.2581	0.1869
1966	2.8058	0.7219	0.2612	0.2225
1967	3.1086	0.8268	0.3207	0.2519
1968	3.021	1.0279	0.7304	0.3437
1969	2.2735	1.2761	0.6704	0.5268
1970	1.5088	1.2147	0.4013	0.532
1971	1.5087	1.0009	0.1929	0.4961
1972	2.0598	0.7333	0.1865	0.3787
1973	2.7088	0.5435	0.5232	0.2695
1974	2.8333	0.5532	0.8709	0.2315
1975	2.3575	0.6553	0.5723	0.2571
1976	2.0002	0.7356	0.5465	0.321
1977	1.6735	0.7385	0.5522	0.3531
1978	1.3031	0.5843	0.3703	0.3284
1979	1.0593	0.4031	0.2379	0.2026
1980	0.95	0.3686	0.2168	0.1636
1981	0.7823	0.3863	0.1955	0.2035
1982	0.688	0.3711	0.1746	0.1891
1983	0.6561	0.3238	0.1305	0.1595
1984	0.9425	0.2846	0.1249	0.1527
1985	1.0726	0.2926	0.1601	0.1478
1986	1.1619	0.252	0.3011	0.129
1987	0.7922	0.2379	0.3766	0.1465
1988	0.6539	0.2093	0.3001	0.1348
1989	0.616	0.3192	0.1729	0.1596
1990	0.7839	0.2805	0.1037	0.0849

The price and cost parameters are from Eide [1987], where the 1983 price of cod is estimated to be 5.10 NKr/kg and the cost per unit marginal fishing mortality the same year, 9.1452 million NKr.

There is assumed to be no costs of selection. According to Flaaten and Larsen [1991], these costs are neglectable.

3. METHODS

On the basis of the four explanations of fluctuations presented above, four different models can be developed to describe the dynamics that cause the observed fluctuations. The aim of this exercise is to isolate the one explanation that tends to be the most important in understanding the dynamics of the fluctuations.

3.1 Environmental variation

The aim of the work of Johan Hjort [1914] was to show that the year by year fluctuations in catch of cod was closely related to fluctuations in the stock size. Stock estimates could only be calculated from catch and it was necessary to have a theory for the interrelation between catch and stock size. Hjort contributed to this by describing and putting together different physical phenomena's that could be easily measured. By comparing data from catch (quantities, liver content, individual weight, estimated age, etc.) with physical data (temperature, salinity, sunspot activity, etc.), Hjort suggested that there was an interdependence.

In the later years there has been carried out little systematically work in this field, as far as the cod stock of the Barents Sea is concerned. Steinshamn [1992] tries to explain the variations in the cod recruitment by variations in temperature in the environment. According to his work about 20% of the variations in recruitment can be explained by variations in temperature.

The environmental variation is a part of a chaotic meteorological system. If the variations in the fish stock are heavily dependent on meteorological variation, long term prognosis of the stock could be strongly effected by error in the initial data set. Although the environmental variation seems to have some influence, it does not seem to be essential.

3.2 The dynamics of the ecosystem

The dynamics of the ecosystem of cod in the Barents Sea have been investigated by the TSB model developed by Flaaten [1988]. The TSB model is a predator-prey model covering three tropic levels of the ecosystem of the Barents Sea, sea mammals, codfish and pelagic herbivorous. Solving the three differential equations of the model, including the catch, turn out to give a prediction of a much more stable stock development than the VPA estimates indicate. The TSB model therefore does not seem to include the most important dynamics behind the observed fluctuations.

3.3 The dynamics of open access fisheries

The cod fishery of the Barents Sea has been an open access fishery during almost the whole period of 1962-1990. A plausible explanation of the main negative trend of the stock size and the annual fluctuations could be the fleet entry-exit dynamics of an open access fishery. A simple entry-exit model is described by Clark [1976] (page 203). The model of Clark was slightly modified by adding a negative growth rate of the cost. Applied on the cod fishery, the modified model was able to reproduce the stock development during the period. The predicted fluctuations of the fishing effort, however, were far more dramatic than the observed variation in the fishing effort during the same period. The fishing effort in this case was assumed to equal the harvest per unit of biomass in stock. Although the open access dynamics seem to explain some of the observed variations during the period, the fleet activity tends to be much more stable than this simple model suggests.

3.4 The dynamics of a single stock

Measuring the strength of one cohort at the age of three years, all the dynamics from 0 to 3 years are hidden. The fecundity is expected to be strictly dependent on the size of the spawning biomass. It is not necessarily such a strong relationship between the spawning biomass and the number of survived three years old recruits to the fish stock. Later studies (e.g. Mehl [1989]) have showed that the cannibalism in the cod stock could have a great impact on the number of three years old cod.

Together with the observations presented in Figure 1 this leads to the following questions: Is it a connection between the strong cohorts and the poor cohorts the following years? Can the fluctuations be due to cannibalism caused by high density and a big proportion young fish?

Let us consider mature and immature to be two different stocks. The recruitment of the mature cod depends of the size of the immature cod stock.

Let x denotes the biomass of the mature stock and y denotes the immature stock. Assuming that the dynamics of the two stocks can be described by a modification of the predator-prey model of May et al. [1979]. Let the marginal growth of the mature stock would be

$$\dot{x} = rx(1-\frac{x}{ay})-h_x, \qquad (1)$$

h_x, being the marginal catch of the mature stock.

The stock size of the immature cod stock is assumed to depend on the size of the mature cod stock. In addition to this it is assumed that the mature stock predates on the immature stock. The marginal consumption of the immature stock is assumed to be bilinear in the size of the two stocks. h_y being the marginal catch of the immature stock, the marginal growth of the immature stock would be

$$\dot{y} = sy(1-\frac{y}{bx})-kxy-h_y \qquad (2)$$

3.4.1 Bioeconomic model

To investigate some economic implications of the assumed symbiotic behavior between mature and immature cod, a simple bioeconomic model has been used. The short-term harvest equation is assumed to be

$$h_i(f_i,i) = f_i \cdot i, \quad \text{when } i \text{ is } x \text{ or } y, \qquad (3)$$

assuming that the fishing mortality (f) is proportional with the fishing effort. A selective fishery in this context is defined as a fishery of mature cod, minimizing the bycatch of immature cod. In a non-selective fishery then, f_x is supposed to equal f_y. The relation

$$\alpha = \frac{f_y}{f_x} \qquad (4)$$

is then assumed to equals 1 in a fishery without selection, and be less than 1 when selection is introduced into the fishery. Theoretically α could exceed 1, having a negative selection, which is minimizing the catch of mature cod when fishing immature.

The total cost (C) of the fisheries of mature and immature cod is assumed to depend both on the selection value (α) and on the fishing mortality (f). The simplest way of doing this, is to assume a selection dependent unit cost of fishing mortality ($c(\alpha)$)

$$C(\alpha, f) = c(\alpha)\cdot f\,. \qquad (5)$$

The total revenue of the cod fisheries (fishing mature and immature cod) is the sum of revenue from mature and immature cod

$$R(f_x, f_y, x, y) = p_x h_x(f_x, x) + p_y h_y(f_y, y)\,. \qquad (6)$$

3.4.2 Equilibrium

From (1) and (3) the net growth of the mature stock is given by

$$\dot{x}(x,y,f_x) = x(r-f_x)(1-\frac{rx}{ay(r-f_x)})\,. \qquad (7)$$

From this it is easy to see that

$$\dot{x} = 0 \quad when \quad \begin{cases} \bar{x} = 0 \\ \bar{x} = \frac{a}{r}\bar{y}(r-f_x) \end{cases}. \qquad (8)$$

The line above x and y indicates that these are equilibrium values, where the net growth in each stock is zero. Similarly the net growth of the immature stock can be derived from (2) and (3)

$$\dot{y} = y(s-kx-f_y)(1-\frac{sy}{by(s-kx-f_y)}). \quad (9)$$

From this the equilibrium values of the immature stock will be

$$\dot{y}=0 \quad when \quad \begin{cases} \bar{y}=0 \\ \bar{y}=\frac{b}{s}\bar{x}(s-k\bar{x}-f_y) \end{cases}. \quad (10)$$

(8) and (10) determine the equilibrium stocks of mature and immature cod:

$$\bar{x}(f_x, f_x) = \frac{1}{k}(s-f_y-\frac{\frac{rs}{ab}}{r-f_x}), \quad (11)$$

$$\bar{y}(f_x, f_y) = \frac{r}{ak(r-f_x)}(s-f_y-\frac{\frac{rs}{ab}}{r-f_x}). \quad (12)$$

3.4.3 Parameter estimation

(1) and (2) are a simultaneous system where the unexplained variables are non-linear combinations of x and y. Using the data set of Table 1 one has to rewrite the equations to discrete time. Using the simple Euler method, the total annual growth of the mature stock will be

$$\Delta x_t = x_{t+1} - x_t \quad (13)$$

The unexplained variables will be stochastic both due to measuring error and other types of uncertainty. There will also be some uncertainty connected to the fitness of the model ((1) and (2)). From the discrete version of (2) and (13) an estimate of the mature stock size year t+1 can be derived from the catch and given stock size of year t

$$\hat{x}_{t+1} = (1+r)x_t - \frac{r \cdot y_t^2}{a \cdot x_t} - h_{x,t} + u_t, \quad (14)$$

u being the error term.

In the same way the estimated size of the immature biomass will be

$$\hat{y}_{t+1} = (1+s)y_t - \frac{s \cdot y_t^2}{b \cdot x_t} - kx_t y_t - h_{y,t} - v_t, \quad (15)$$

v being the error term.

The parameters of (14) and (15), a, b, r, s, and k, are estimated simultaneously by minimizing the relative sum of squares

$$Rel.SSQ = \sum_t ((\frac{\hat{x}_t - x_t}{x_t})^2 + (\frac{\hat{y}_t - y_t}{y_t})^2). \quad (16)$$

4. RESULTS

The obtained estimates are given in Table 2.

Table 2. Estimated values of the parameters of (14) and (15).

Parameters and DW-estimators	OLS-estimates from (14) and (15)	Parameter-values obtained by minimizing (16)
r	0.5951	0.6728
A	1.2834	1.1880
s	0.4946	0.5003
B	14.3599	8.7608
K	0.2959	0.2023
DW-est. of (4)	1.12396	1.03396
DW-est. of (5)	0.8127	0.7919
$DW_{L5\%}$	1.20	
$DW_{U5\%}$	1.65	

Figure 4 shows the simulated total catches of both mature and immature cods, using the parameter values of Table 2 and starting out with the initial values of 1962 (Table 1). The annual fishing effort of the period are assumed to equal the annual catch per unit of biomass in stock the same year.

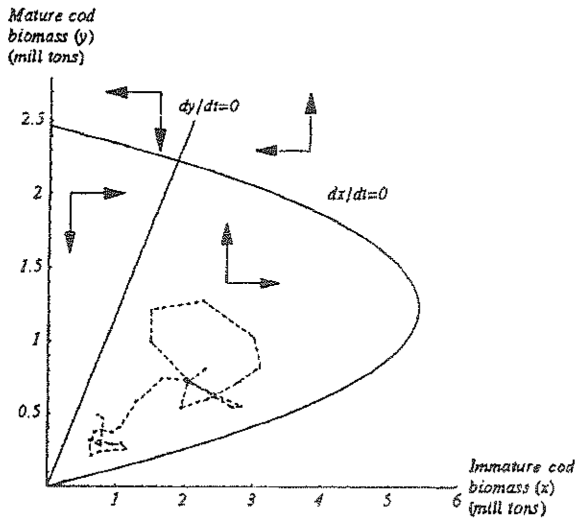

Figure 2. Phase plot of the isoclines of (1) and (2) (solid lines), and the estimated stock biomass history of the period 1962-1993 (ICES estimates). The parameter values of the right column in table 2 have been used.

The simulations are done using the parameters obtained by minimizing (16) (Table 2). The initial values (x = 2.3110 and y = 0.8127) were the VPA estimates of the biomasses of immature and mature cod of 1962. The simulations were done by solving the differential equations (1) and (2) corrected by the estimated fishing mortalities (f) of the period.

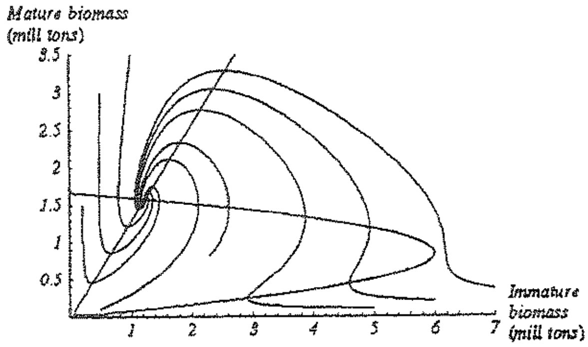

Figure 3. Phase plot of the isoclines of (1) and (2) and tracks from different positions towards the natural equilibrium.

The maximum sustainable yield of the cod stock is obtained by a mixed fishery of immature and mature cod (Figure 5). The biological production of the stock will be lower in a perfect selective fishery of mature cod. This is of course because of the increased cannibalism when the density of immature cod increases.

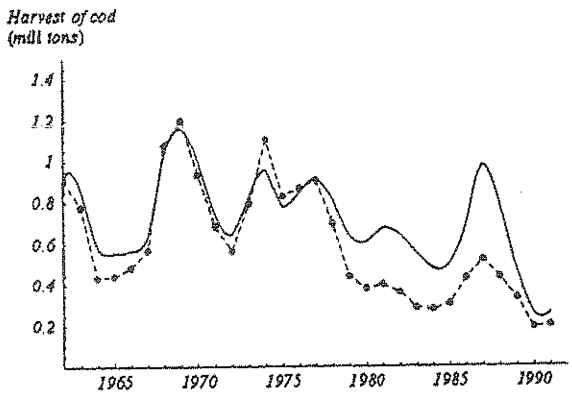

Figure 4. Simulated total catch of immature and mature cod from 1962 to 1991 (solid line) and actual catch (dotted line) over the same period.

A maximum economic yield of 0.9 billion NOK (Norwegian Kroner) is obtained by a non-selective fishery, according to the costs and prices presented above (Figure 6). The market price per kilo immature and mature cod is supposed to be identical. If the market price of mature cod exceeds 105% of the price of immature cod, a selective fishery will be more rentable than a non-selective fishery.

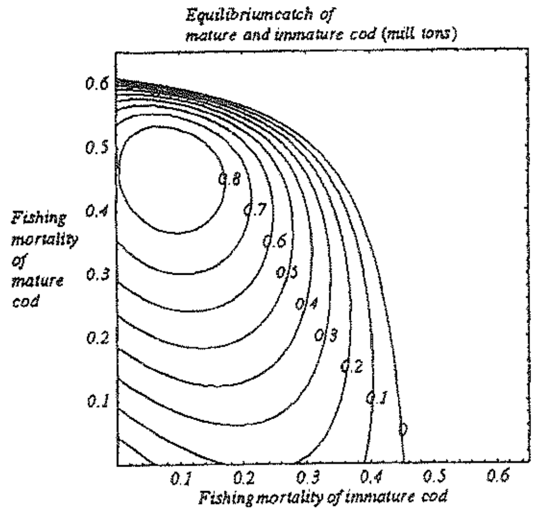

Figure 5. Equilibrium catch of cod with given combination of fishing effort on the immature and mature part of the stock.

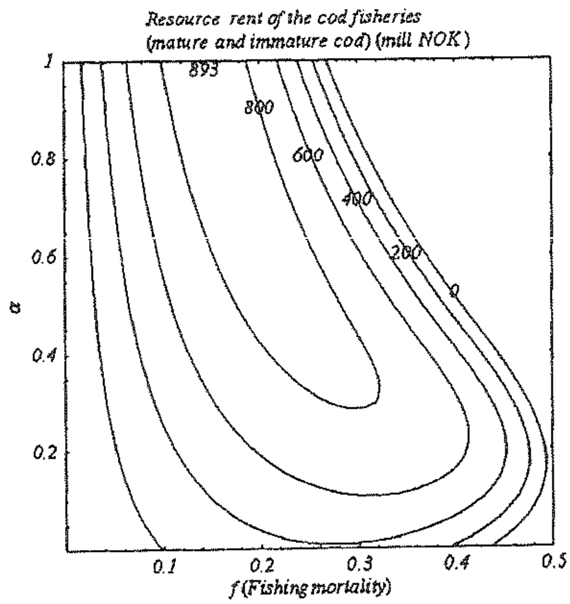

Figure 6. Resource rent of the cod fisheries for given combination of fishing mortality and the selection factor α.

5. CONCLUSION

The separation of the cod stock into one mature and one immature part is motivated from the observed cannibalistic tendency of mature cod. The simple model presented in this paper gives a surprisingly good correspondence to historical catches and stock estimates from tuned VPA runs. The simulated figures of the eighties, however, differ from the historical data. According to the model it is a significant decline in cannibalism during this years. The term *kxy* in (2) gives the predicted quantity immature cod consumed by mature cod. From a level of 0.3 million tons in the mid seventies, the predicted annual consumption of immature cod falls down to less than 50,000 tons during the eighties. Then probably the reliability of the model is reduced.

Earlier much focus has been put on the recruitment problem of the cod stock. The week relationship between spawning biomass and number of recruits to the stock, has been an argument of involving more complex models. Especially environmental changes have been believed to play a role here. The findings in this paper are that by including the cannibalistic behavior, the explained variations are increased significantly.

If the cannibalistic behavior is of such an importance for the cod dynamics, the management goal of reducing catch of immature cod could be problematic from a resource economic point of view. However, this will depend on the market value of mature and immature cod.

The importance of the cannibalistic behavior in the cod stock is illustrated in Figure 3, showing a very dynamic system. Even small environmental changes could cause great fluctuation independent of the fishing effort. The dynamics would probably be even larger adding the lag-effect of variations in the recruitment to the cod stock.

The model, which has been used in order to describe the dynamics of the cod stock, could more generally be used to describe a symbiotic relationship between two species.

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