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Abstract

A biological model, belonging to the Beverton and Holt age-structured family, for the Norwegian spring spawning herring (NSSH) is simulated, the outcome of which compares well with actual data on the fishery. This model is then combined with an economic model to help investigate how optimal a management policy of constant fishing mortality will be for a fishery such as the NSSH, which has a highly fluctuating stock biomass. For the range of constant values of fishing mortality explored, and a time horizon of the simulation of 20 years, a constant fishing mortality of 0.15 turns out to be economically optimal. It should be noted that this result is sensitive to variations in the assumptions underlying key variables of the fishery. For example, when a constant rather than a variable recruitment was assumed, a different optimal fishing mortality rate was obtained.

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0. INTRODUCTION

The main objective of this paper is to develop a model rooted in actual historical data for the Norwegian spring spawning herring (NSSH), which can be used to investigate the policy implications of management strategies. Traditionally, modelling of the biology of fish has taken two main directions: first, the so-called lumped parameter models of the Schaefer type (Bjørndal and Munro, 1998) and second, the Ricker (1958) and Beverton and Holt (1957) age-structured models. In general these two model types are the most commonly applied in the study of commercial fisheries.

Historically, the Norwegian spring spawning herring is a fish stock with extremely variable year-classes. It also has individual fish that can live for up to 20 years. It may thus be appropriate to employ a model that includes age-structure and recruitment of year-classes when modelling the fishery. Considerable attention has been given to the management of age-structured populations in the literature (see, for example, Clark, 1990; Getz, 1985, Sumaila, 1995). This paper will also employ this type of modelling framework with modifications built in to capture the special features of the NSSH.

A detailed bioeconomic model for this fishery is developed and estimated on the basis of biological and economic data. The NSSH was driven to near extinction in the 1960s as a consequence of the open access nature of the fishery, which was exacerbated by the development of new harvesting technology and the straddling nature of the stock. The bioeconomic model developed will be used to simulate optimal management strategies for the fishery.

The paper is organised as follows. In the next section, a brief discussion of the biology of the stock is given. This is followed with a presentation of the development of the stock biomass and landings from a historical point of view. In section 2, we discuss some management issues in a sole ownership setting. We then formulate the population dynamics model in its more general form in section 3. In section 4, a model of population dynamics is first presented and simulated. Then an optimisation model that combines both biology and economics is developed and estimated. Section 5 discusses these results and concludes the paper.

1. THE BIOLOGY OF THE NORWEGIAN SPRING SPAWNING HERRING STOCK

To enhance our understanding of the NSSH (*Clupea harengus*), a brief review of the biological characteristics of the fish stock is in order. The NSSH are a pelagic stock which feed on plankton. Pelagic fish are characterised by the fact that their nourishment is limited to a couple of months in spring and summer, while zooplankton flourish. After this phase is over and the small copepods seek deeper water, the fish end their feeding and begin the migration to wintering areas where they live on the food reserve and the gonads evolve (Bjørndal *et al*., 1998).

The herring spawn along the West Coast of Norway from February through April. The spawning areas are located at a depth of between 50 and 150 metres, have a gravelled bottom and good water replacement, with temperatures between 4-7 degrees Celsius. The eggs stick to the gravel and hatch after approximately three weeks, and then the larvae come to the surface. During the first week, the larvae can live on the yolk-sack: afterwards they feed on the eggs and larvae of small copepods. The larvae phase lasts for two months, and during this period they can be carried by the current over considerable distances along the coast northward to the North Atlantic and the Barents Sea. After about two months, when the herring are 3.4-4.5 centimetres long, the conversion from larvae to fry occurs (Bjørndal *et al*., 1998).

The juvenile herring reside in the maturing area along the Norwegian coast, in the Barents and the Norwegian Seas until they are sexually mature. Prior to about 1970 the herring matured when they were 5-6 years old. Now they mature for the first time at an average age of four years.

<u>Stock Development</u>

Based on available data on the spawning stock of the NSSH for the 1950-1997 period, we study the historical development of the stock by plotting the time series of observations (Figure 1). The International Council for the Exploration of the Sea (ICES) considers a spawning stock of 2.5 million tonnes as the minimum level to guarantee good recruitment (Minimum Biological Acceptable Level or MBAL) (Bjørndal *et al*., 1998).

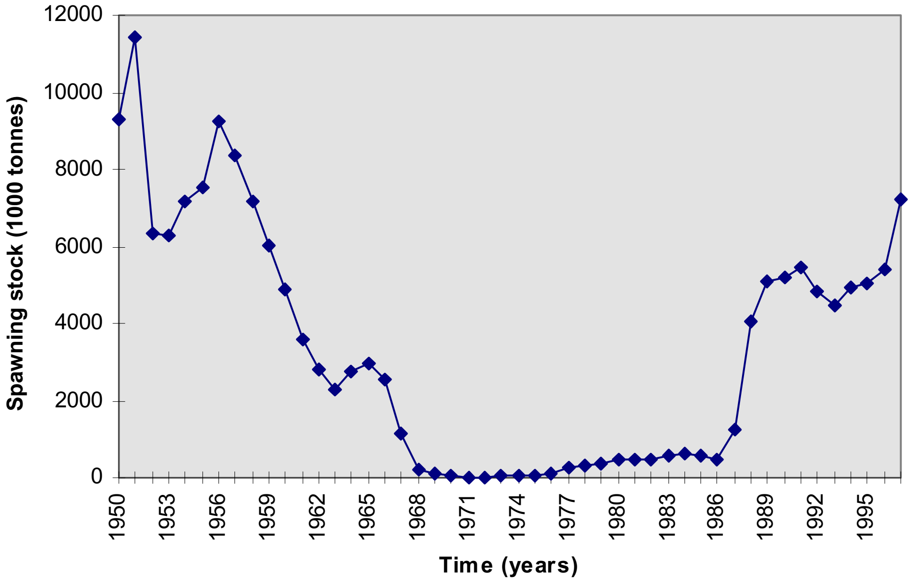

Figure 1: Spawning Stock Biomass of Norwegian Spring Spawning Herring 1950-1997 (1000 tonnes). Source: (Bjørndal *et al.*, 1998), Directorate of Fisheries (1996).

From Figure 1, we observe that the spawning stock of the NSSH was between 6 and 11 million tonnes in the 1950s. The stock was reduced to below 3.0 million by 1965, and from 1965-1969, the mature stock was almost depleted due to over-fishing. A small part of the fish survived as juvenile herring, and spawned for the first time in 1973 (Bjørndal *et al.*, 1998).

In the early 1970s, there was almost no herring spawning along the Norwegian coast. As a result the production of larvae was minor, and the 1970-1972 year-classes were insignificant. There was almost a total collapse of the mature stock. Strong regulations were implemented to allow an increase in the spawning stock, although even with such measures the increase was slow. Nevertheless, there was a steady increase during the period from 1973-1984. However, there was a downturn in 1985 and 1986 which coincided with an increase in herring landings.

Two components of juveniles survived the hard fishing of the late 1960s. One component used the Barents Sea or the northeastern Norwegian Sea as a maturing area. The other component had its maturing area off the west coast of Norway, or in the border between the

Norwegian Sea and the North Sea. The northern component is believed to have been the largest. From 1973-76 the stock was around 40,000 tonnes. However, due to recruitment from the 1973-76 year-classes, the spawning stock more than doubled from 1976-77, and reached a level of over 100,000 tonnes. The spawning stock then increased slowly every year to 1984. In the years between 1985 to 1987, landings increased and the result was a reduction in the spawning stock. However, at the end of the 1980s the spawning stock increased substantially.

The spawning stock recovered to a level between 4.5-5.5 million tonnes in the 1990s, i.e., within safe biological limits according to the ICES (1996). The 1991 and 1992 year-classes were strong, but the next three year-classes are believed to be weak. As a consequence, the recruitment to the spawning stock in 1996-98 was good, but it is subsequently expected to decrease.

Landings of herring

Figure 2 shows that the landings of herring in the period from 1950 to 1995 tracked the stock size. In the 1950s, the annual landings were about 10-15% of the stock which represented moderate exploitation. However, due to technological progress in the 1960s, i.e., the introduction of the sonar and the powerblock, the fishery became much more effective (Bjørndal, 1988). Moreover, as herring is a straddling stock, migrating over vast areas in the North Atlantic (see Section 2), fishermen from numerous countries targeted the stock. This led to an incredible increase in the harvesting of the herring. The 1966 landings were about two million tonnes from a total stock of 2.6 million tonnes, a rate of 77%. In the subsequent years, the harvest rate increased to about 90%. The stock collapsed at the end of the 1960s due to the high harvesting, coupled with high catches of immature herring. After the collapse a herring moratorium was introduced; only a limited fishery for human consumption was permitted. The goal was to rebuild the spawning stock to a level that would ensure a long term acceptable recruitment.

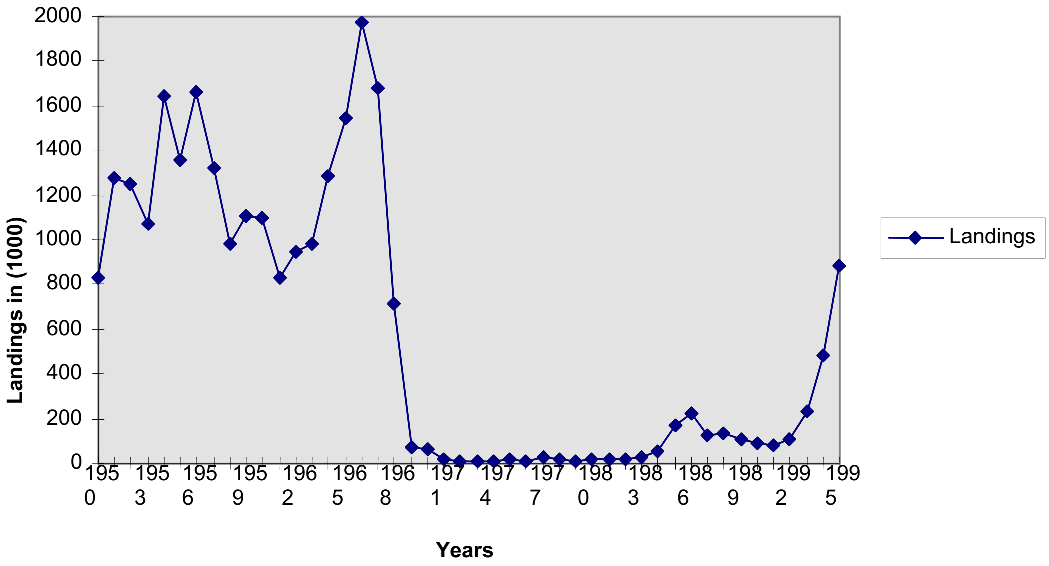

Figure 2: Landings of NSSH in the period 1950-95 (1000 tonnes).
Source: Bjørndal *et al*., (1998).

2. MANAGEMENT OF THE NSSH

The objective of a sole owner should be to manage the stock in a way that will give a stable and as high as possible long-term biological and economic yield (Conrad and Clark, 1987). According to the Advisory Committee on Fishery Management (ACFM) this can be achieved by keeping the spawning stock biomass (SSB) over the Minimum Biological Acceptable Level (MBAL) of 2.5 million tonnes. Such regulation will prevent the recurrence of a stock collapse like the one at the end of the 1960s.

The NSSH is potentially one of the largest and most valuable fish stocks in the world. As a straddling stock, it is harvested by Norway, Iceland, the Faroe Islands, Russia and the EU. The migration pattern for the NSSH consists of four phases. The migration begins in the spawning area, proceeds to the maturing area for juveniles, then to the feeding area and ends in the wintering area. These areas are partly in the Exclusive Economic Zones of the coastal states and partly in the high seas, although the migratory pattern is observed to have changed over time. The implications of the straddling nature of the stock for management are analysed in a game theoretic context by Bjørndal *et al.* (2000).

Conservation policy for marine resources is based on various technical measures and the setting of total allowable catches (TACs). TAC is a tool to control harvesting of the stock, while technical measures are meant to control fishing mortality in younger year-classes. The NSSH are managed by regulating both catches (output-control) and catch capacity (input-control). Catches are restricted by fixing a TAC and dividing it up in quotas among the involved nations. Catch capacity is limited by fixing authorised total allowable effort (TAE) by licenses, number of vessels, and types of gear. Total quotas, their distribution among nations, and transfer of fishing rights are agreed to in the annual fisheries negotiations (see Bjørndal *et al*., 1998).

3. THE POPULATION DYNAMICS

In this section, a model of population dynamics, representing changes in biomass and cohort sizes of the NSSH stock, will be constructed. The goal here is to formulate a biological model of growth and mortality of recruited year-classes, which will reflect the dynamics of the stock as a result of natural mortality, growth and harvesting. The population dynamic model will be constructed using the Beverton-Holt population dynamic model and the structural stock-recruitment models estimated by Patterson (1998). The total biomass relation will be derived using the average weight of individuals in each cohort at time t and the number of fish in the cohort. The total yield function will also be derived. Simulations of the Beverton-Holt model for the stock dynamics will be performed.

The Beverton-Holt model has been extensively used in the fisheries management environment (Clark, 1990). It is characteristically an age-structured model, i.e., the fish population consists of a number of different year-classes or cohorts. Its relevance for modelling long-lived species, the fishable stock of which consists of several age groups and its importance in predicting the effects of changing gear selectivity (see Sumaila, 1997), or the recruitment of exceptionally good year-classes, has been noted (Hannesson, 1978). The choice of this model for the analysis of the NSSH fishery is not arbitrary because this stock is long-lived consisting of many cohorts and is unusual in having extremely variable year-class strength. In addition, a decennial cycle hypothesis is made in Anon (1996a) where it is stated that 'the time series shows that there has always been a period of up to 10 years between years of good recruitment' (Patterson, 1998, p.7).

Let the number of fish of each cohort i at time t be a function of the original number of recruits to that cohort at time t-i+σ, $R_{t-i+\sigma}$, where σ is the age of recruitment and the total mortality of the fish composed of the fishing mortality, $F_{i,t}$ and natural mortality $M_{i,t}$:

$$N_{i,t} = R_{t-i+\sigma} \exp(-\sum_{j=\sigma}^{i-1}(F_{j,t-i+j} + M_{j,t-i+j})) , \qquad (1)$$

The spawning stock biomass is a fraction of the total biomass of the population at any given time. Let $p_{i,t}$ be the proportion of mature fish of age i, then the spawning stock biomass at time t is given by

$$B_t = \sum_i p_{i,t} N_{i,t} \overline{w}_{si,t} \qquad (2)$$

where $\overline{w}_{si,t}$ is the average weight of the fish at spawning. Estimates of the proportion of mature fish for the NSSH are found in Patterson. For the analysis at hand, we shall use the available information on weights in the fishery in Patterson (1998).

In general, catch in numbers from each cohort at time t is a function of stock number of the year-class and the fishing mortality at that time. The instantaneous yield in biomass is defined as that part of the change in biomass resulting from fishing mortality $F_{i,t}$ and is written as

$$Y_t = \sum_i C_{i,t} \overline{w}_{i,t} , \qquad (3)$$

where the catch is given by

$$C_{i,t} = \frac{F_{i,t}}{(F_{i,t} + M_{i,t})} R_{t-i+\sigma} (1 - e^{-(F_{i,t}+M_{i,t})}) e^{-\sum_{j=\sigma}^{i-1}(F_{j,t-i+j}+M_{j,t-i+\sigma})} . \qquad (4)$$

The total yield is now expressed in terms of the number of fish, the instantaneous mortality, recruitment and the average weight of the fish. In the following section, we shall discuss the weight function to be used in the analysis.

Knowledge of the weight relations is vital in calculating the total biomass of the spawning biomass and the yield from the stock. The tradition among fisheries researchers is to use average weight of the stock. Estimates of weights at age in stock and catches for the fishery are calculated in Patterson (1998).

To specify the stock-recruitment function, it may be plausible to assume that recruitment is in some way related to the size of the spawning stock. For this analysis, we shall use the models estimated in Patterson (1998) in which four different models were estimated. Patterson fits the Beverton-Holt and Ricker models with and without assumption of autocorrelation in the errors. In this analysis, the model without assumption of autocorrelation is used because it is simpler and has also been used by others.

Table 1. Parameters of the Beverton-Holt Recruitment Function

Beverton-Holt, Uncorrelated Errors	Beverton-Holt, Autocorrelated Errors
A 32.4592041	31.636972
b 3044867.32	3284059.9
g -	-0.09324
Variance 1.802	Variance 1.6937

Source: Patterson (1998, Table 5.1)

Natural mortality is composed of several parts, the most significant being mortality due to predation, senescent and spawning stress mortality (Steinshamn, 1992). The ICES working Group assumes that the natural mortality of adult fish for the NSSH are M=0.12 for ages three to 14 onwards, except in the case of the year-classes of 1977 to 1987 where it is assumed to be M=0.23. This additional mortality was attributed to an outbreak of the disease *Ichthyophonus hoferi* in the stock (Anon, 1996b). Calculations in Patterson lead to the conclusion that the value of M=0.13 is appropriate for recent years, since there appear to be no justification for the assumption of additional disease-induced mortality is concluded.

It is an established fact that natural mortality varies inversely with age, being very high at the egg and larval stage and quite low at the adult age. The mortality rates for juvenile fish for the NSSH are of the order of 1.56 at age 1 to 0.54 at age 2 (see Barros, 1995).

4. A BIOECONOMIC MODEL FOR NSSH

The model of population dynamics will now be simulated for the period of 1986-1995 and the results will be compared with actual data in order to evaluate the performance of the model. To carry out the simulations we use the special forms of the relations derived in the previous sections. The following assumptions are made here: the natural mortality $M_{i,t}$ is set equal to 0.9 for fish of ages 0-2 and 0.15 for ages 3-16 for all time periods, while the fishing mortalities $F_{i,t}$ are allowed to vary over age and time. The data for the simulation consist of recruitment at age zero, number of fish at time zero (1986) for each year i (i=0,1,.....,16), the natural mortality $M_{i,t}$ and fishing mortality $F_{i,t}$ at age i and year t, the weights at age in spawning and in catches, all taken from Patterson (1998), except $M_{i,t}$ and $F_{i,t}$. Recruitments for the 1986-95 are values found in Patterson 1998 (Table C4). Data on weights at catch and spawning and maturity ogive are obtained from historical data on the stock. These are assumed fixed throughout the simulations and are different for each age.

The results of the simulation of the population dynamics for the NSSH are shown in Figures 3 and 4. The simulated biomass is seen to follow closely the actual values observed but is always lower. Thus, the agreement is more qualitative rather than quantitative. From Figure 4, the model tracks the observed landings very well except for the initial year. The simulated values are somewhat higher between 1986-1990, almost equal to actual values between 1991-1993, while they are lower in 1994 and 1995.

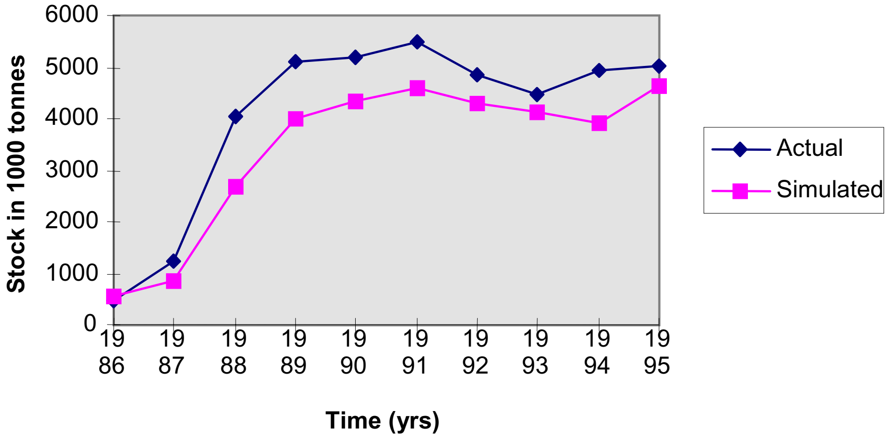

Figure 3: Actual and simulated spawning stock (1986-95).

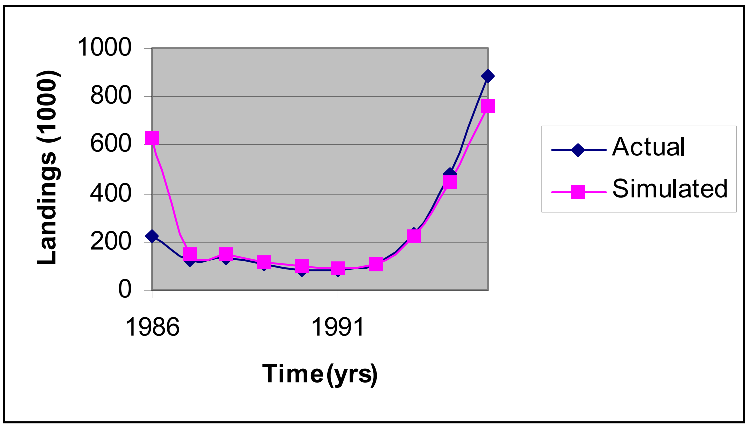

Figure 4: Actual Landings and Simulated Yield 1986-95.

An Optimisation Model for the NHHS

We now combine the model of population dynamics with an economic model, and then perform simulations in order to investigate some of the policy implications of a strategy of maintaining a constant fishing mortality rule, i.e., constant in terms of both time and across year classes. The aim here is to estimate the optimal constant fishing mortality over a pre-set time horizon. For this analysis, the price of fish per unit and the harvesting costs are assumed to be constant. Given these assumptions, the annual profits are given by

$$\pi_t = (p - c) Y_t \qquad (5)$$

where p is the constant unit price of fish, while c is the unit cost. Hence, the total discounted profit (TR) over the time horizon of the model (T) or the present value of the annual profits is defined as

$$TR = \sum_{t-1}^{T} \left(\frac{1}{1+r} \right)^{t} \pi_{t} \qquad (6)$$

where r is the annual discount rate. It should be noted that TR is calculated over a range of possible fishing mortality rates. This range includes the optimal rate which yields the maximum profits subject to the population dynamics of the model.

The assumption of constant price is common in the fisheries economic literature (Bjørndal and Munro, 1998). Here it is justified by the fact that Norwegian spring spawning herring is but one of many sources of herring worldwide. Hence, the supply of NSSH alone will not be enough to influence the global price of herring.

The justification for assuming a constant cost per unit harvested is that we are dealing with a schooling fishery. Schooling fish contract their distribution as stock size is reduced, with the size of schools remaining more or less unchanged. Thus, with modern fish finding equipment, harvesting can remain profitable virtually until the stock is driven to extinction (Bjørndal 1988). The development of this fishery under open access conditions, as described above, is clear evidence that this is the case. Evidence to the same effect is provided by Bjørndal and Gordon (2001) who undertook an empirical analysis of the cost function for three vessel groups in the Norwegian spring spawning herring fishery, where they found that basically cost was constant per unit harvested.

<u>Data and Results</u>

The time horizon of the simulations is 20 years due to the sensitivity of the recruitment function used in this study. The simulations were performed assuming the net unit price, p - c = 1 NOK per kg, based on Bjørndal *et al*. (1998), setting r = 0.07 and using the stock-recruitment function estimated above. In the biological model, a selectivity rate S_i, describes how vulnerable each age class is subject to gears. Knife-edge selectivity is applied to simplify the analysis. The groups are divided into two and the selectivities are given the values $S_i = 0.0$

for ages between zero and three and $S_i = 1.0$ for the remaining ages. This is plausible because all age groups are not equally vulnerable to fishing gear.

Graphs of discounted profits and total spawning biomass for different fishing mortality rates are shown in Figure 5. The solid line is discounted profits. It is observed to increase sharply as the fishing mortality rate increases. The profits peak where the fishing mortality is equal to 0.15. The dotted line is the total spawning biomass scaled by 10. The curve decreases sharply for fishing mortalities between zero and 0.4 and is reduced to almost zero for F = 0.8.

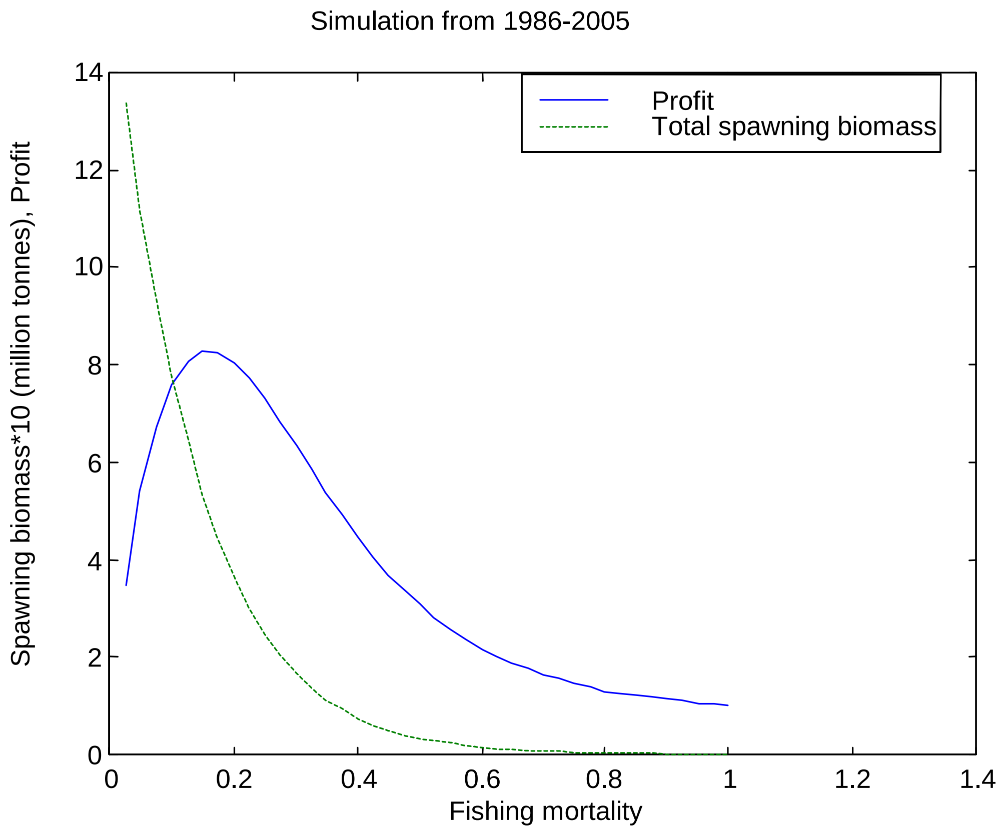

Figure 5. Discounted Profits (Billion NOK) and Total Spawning Biomass for Different Fishing Mortalities.

The annual spawning biomass and the annual total yield for the optimal constant fishing mortality are graphed in Figure 6. The chart shows the optimal (F = 0.15) spawning stock (high bars) and the yield (short bars) for the period 1986 through 2005.

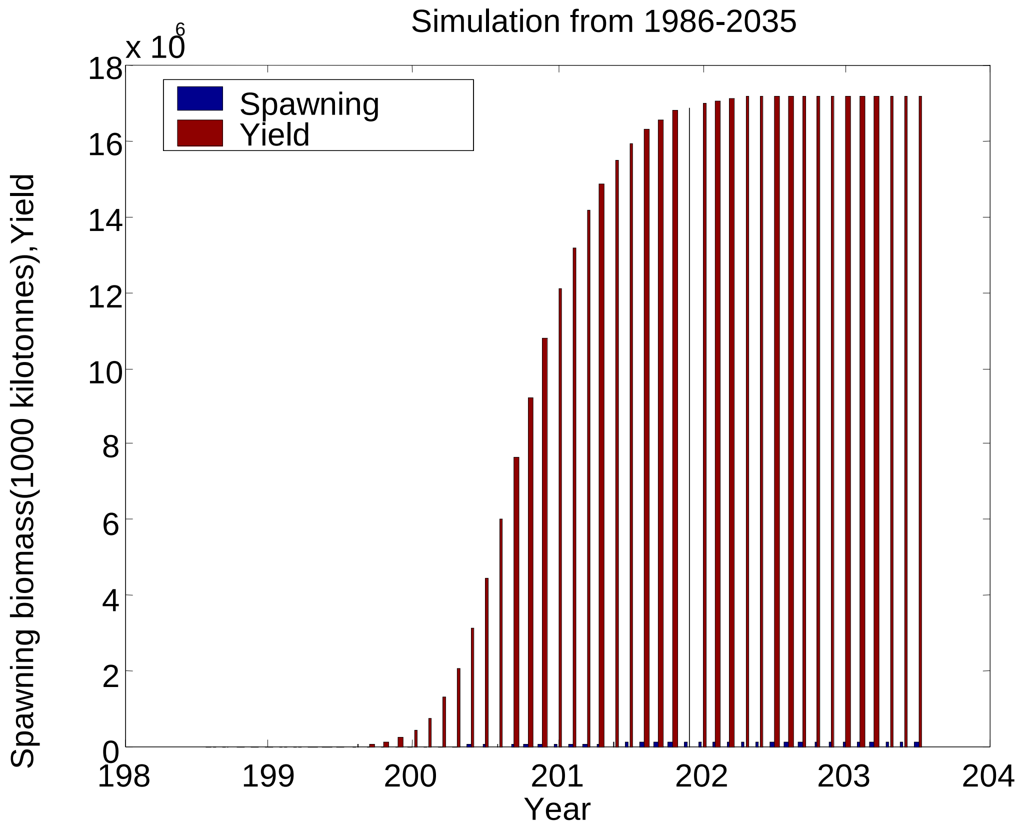

Figure 6: Annual Spawning Biomass and Yield for F=0.15.

The spawning biomass and the yield both increase over the period of simulation as is observed above. The percentage of the stock removed due to human predation is fixed to below 20 percent. From the above it can be seen that for this model, if harvesting is undertaken at the fixed rate of F = 0.15, *ceteris paribus*, in about a decade the stock would more than quadruple.

It is important to note that the optimal fishing mortality rate is sensitive to the form of the recruitment function. Sensitivity analysis shows that using the actual data for the spawning stock biomass in Patterson yielded a slightly higher optimal fishing mortality compared to when other data are used. Similarly, when a constant recruitment was assumed, different optimal fishing mortality rates were obtained. Furthermore, increasing the time horizon of the simulation results in a decrease in the fishing mortality and vice versa. An important caveat regarding the use of the recruitment function in Patterson is that it tends to overestimate the predictions of the zero age group and therefore does not appear very reliable when used for long time horizons.

Next we consider the result when using the actual values of recruitment (age zero) in the simulation (Figure 7). Available values from 1986-1996 were used, while the mean value of 1993-1996 was used for the remaining period since we do not have any observations. That is, for the years where we have no observations, the mean value of the 1993-1996 was used, which means a constant recruitment is assumed. The solid line in Figure 7 is the profits while the broken line is the total biomass. The shapes in this figure are similar to the ones in Figure 5, except that the increases and decreases are rather more gentle than in the latter. The results indicate a higher optimal fishing mortality of F = 0.425 compared to the previous case when selectivity and constant natural mortality are used.

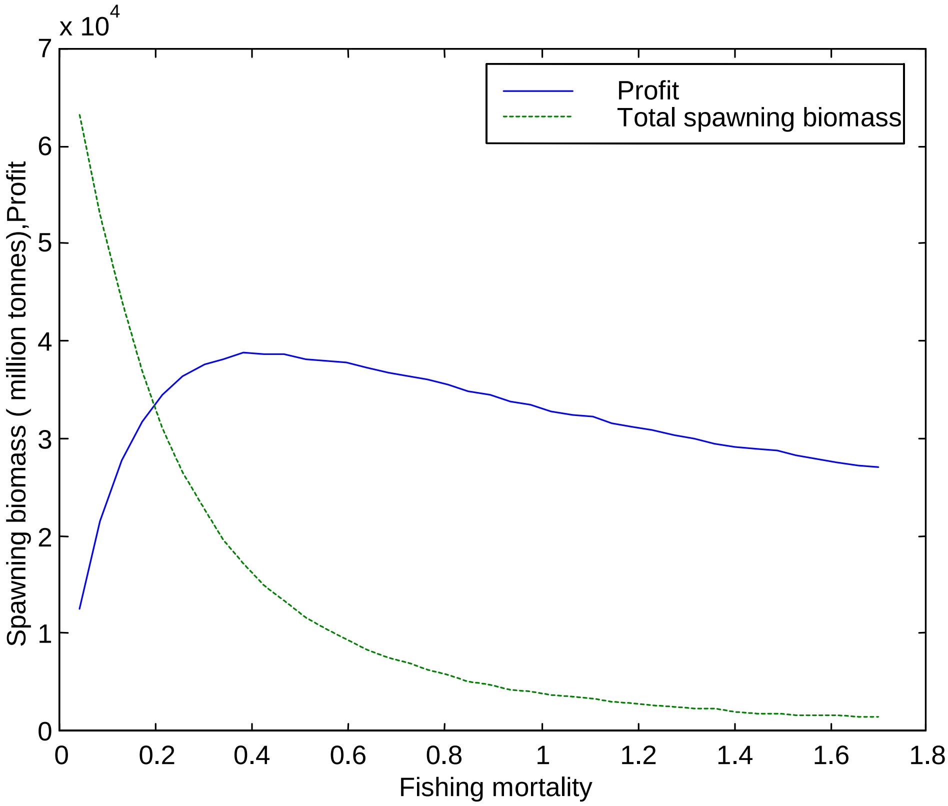

Figure 7. Simulated Profits (Billion NOK) and Spawning Biomass for Different F-Values. Actual Recruitment for 1986-96; Average Recruitment for 1993-96 used for 1997-2005 Period

We have also undertaken a sensitivity analysis for changes in some of the biological parameters (see Table 2). In particular, the natural mortality rate (M) is set equal to 0.15 for all yearclasses. Moreover, there is no selectivity in the fishery. The optimal fishing mortality has been estimated for different simulation periods, all starting in 1986 (see Table 3). For the simulation period 1986-2006, the optimal fishing mortality is 0.082. Optimal F increases in the simulation period and is 0.133 for a simulation period of 100 hundred years (1986-2006). The lower optimal F-values, as compared to the initial cases investigated, can be explained by the changes in the biological parameters values.

Table 2: Assumptions and parameters for the sensitivity analysis.

Year class	spawning fraction	selectivity	natural mortality
0	0.0	1	0.15
1	0.0	1	0.15
2	0.0	1	0.15
3	0.0	1	0.15
4	0.1	1	0.15
5	0.2	1	0.15
6	0.3	1	0.15
7	0.9	1	0.15
8	0.9	1	0.15
9	0.9	1	0.15
10	0.9	1	0.15
11	0.9	1	0.15
12	0.9	1	0.15
13	0.9	1	0.15
14	0.9	1	0.15
15	0.9	1	0.15
16	0.9	1	0.15

Table 3: Results of sensitivity with respect to simulation interval.

Interval	Optimal fishing mortality
1986-2006	0.082
1986-2016	0.105
1986-2026	0.118
1986-2086	0.133

5. CONCLUSION

We have traced the historical development of the Norwegian spring spawning herring, and showed that the stock size can vary substantially over time. The spawning biomass of the NSSH ranged between near extinction in the late 1960s/early 1970s to a high of over 11 million tonnes in the early 1950s. The catches of NSSH tracked this development, with extremely high proportions of the biomass harvested in the 1960s. For instance, in 1966 two million out of a total standing biomass of 2.6 million tonnes were caught. Clearly, such a high catch rate was bound to be followed by a crash of the stock as the case turned out to be.

Focusing our attention on the high variability of the stock, we developed a model of population dynamics for the NSSH based on the Beverton and Holt age structured model. Simulations of the biomass and landings of herring were carried out, and compared to the actual stock and landings for the years between 1986 to 1995. Our biological model for the NSSH captures reasonably well the variable behaviour of the stock over these years. This biological model was then extended to include economic parameters, and applied to investigate management policy for the Norwegian spring spawning herring.

The analysis shows that the optimal constant fishing mortality for herring is $F = 0.15$. It should, however, be noted that the optimal constant fishing mortality determined is sensitive to the form of the recruitment function assumed. In other words, whether we assume constant or variable recruitment will affect the constant catch rate picked out by our model to be the optimal one.

Norwegian spring spawning herring is a schooling stock. Schooling fish stocks are prone to overexploitation under open access conditions. For spring spawning herring this is compounded by the straddling nature of the stock, which means that spring spawning herring can be targeted by fishermen from many countries. Proper management of the fishery is thus required for the sustainable exploitation of the stock and in order to avoid a new stock collapse. For this reason, analyses on the management of a fishery, such as this one, take on added significance.

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