A Bioeconomic Analysis of the Norwegian Spring Spawning Herring (NSSH) Stock

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Abstract *A biological model belonging to the Beverton-Holt age-structured family for the Norwegian spring spawning herring (*Clupea harengus*) (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 simulation time horizon 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 variable recruitment was assumed, a different optimal fishing mortality rate was obtained.*

Key words Bioeconomic model, herring optimal management.

JEL Classification Codes Q57, Q22, Q28.

Introduction

The main objective of this paper is to develop a model rooted in historical data for the Norwegian spring spawning herring (*Clupea harengus*) (NSSH) that can be used to investigate the policy implications of management strategies. Traditionally, modeling of fish biology 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 NSSH 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

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to employ a model that includes age-structure and recruitment of year classes when modeling the fishery. Considerable attention has been given to the management of age-structured populations in the literature (Clark 1990; Getz 1985; Sumaila 1995). This paper employs an age-structured modeling framework with modifications built in to capture the special features of the NSSH.

A 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 is used to simulate optimal management strategies for the fishery.

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

The Biology of the NSSH

To enhance understanding of the NSSH, 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, when zooplankton flourish. After this phase is over and the small copepods seek deeper water, the fish end their feeding and begin their migration to wintering areas where they live on food reserves and where sexual maturation takes place (Bjørndal *et al*. 1998).

The herring spawn along the West Coast of Norway from February through April. The spawning areas are located in areas with depths between 50 and 150 metres that have a gravelled bottom and good water replacement, and temperatures between 4–7 degrees Celsius. The eggs stick to the gravel and hatch after approximately three weeks. The larvae then 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 larval phase lasts for two months. 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 at an average age of four years.

Stock Development

Based on available data of the NSSH spawning stock for the 1950–97 period, we study the historical development of the stock by plotting a 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).
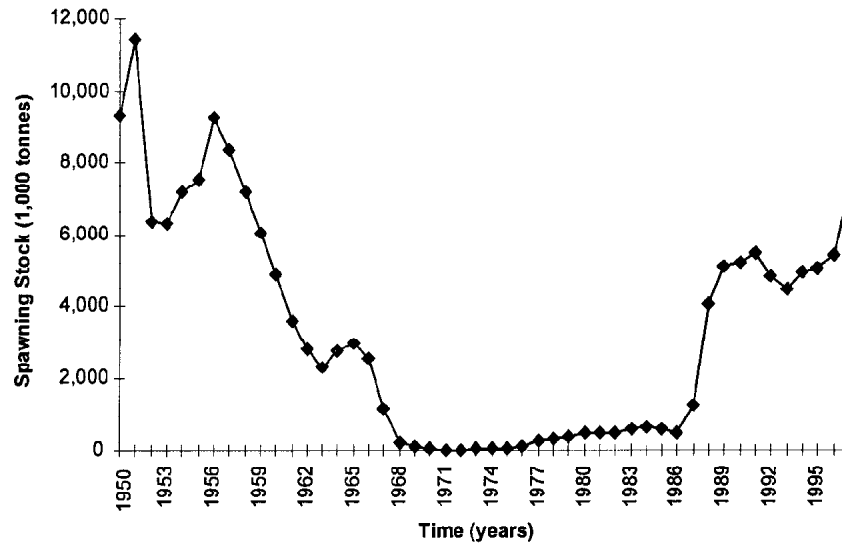
Figure 1. Spawning Stock Biomass of NSSH 1950–97 (1,000 tonnes)
Source: Bjørndal *et al*. (1998); Directorate of Fisheries (1996).

From figure 1, we observe that the NSSH spawning stock was between 6 and 11 million tonnes in the 1950s. The stock was reduced to below 3.0 million by 1965, and from 1965–69, the mature stock was almost depleted due to overfishing. A small segment of the fish population survived 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 1970–72 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 intense 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 on 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. Between 1985 and 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 (ICES 1996). The 1991 and 1992 year classes were strong, but the next three year classes were weak. As a consequence, the recruitment to the spawning stock in 1996–98 was good, but it was subsequently expected to decrease.

Herring Landings

Figure 2 shows that herring landings from 1950 to 1995 tracked the stock size. In the 1950s, annual landings were about 10–15% of the stock, which represents 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 that migrates over vast areas of the North Atlantic, fishermen from numerous countries targeted the stock. This led to an incredible increase in the herring harvest. The 1966 landings were about two million tonnes from a total stock of 2.6 million tonnes, a rate of 77%. In subsequent years, the harvest rate increased to about 90%. The stock collapsed at the end of the 1960s due to 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 long-term, acceptable recruitment.

Management of the NSSH

The objective of a sole owner should be to manage the stock in a way that will provide a stable, long-term biological and economic yield (Conrad and Clark 1987). According to the Advisory Committee on Fishery Management (ACFM) of ICES, this can be achieved by keeping the spawning stock biomass (SSB) over the Minimum Biological Acceptable Level (MBAL) of 2.5 million tones (ICES 1996). Such regulation will prevent the recurrence of a stock collapse similar to that 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,
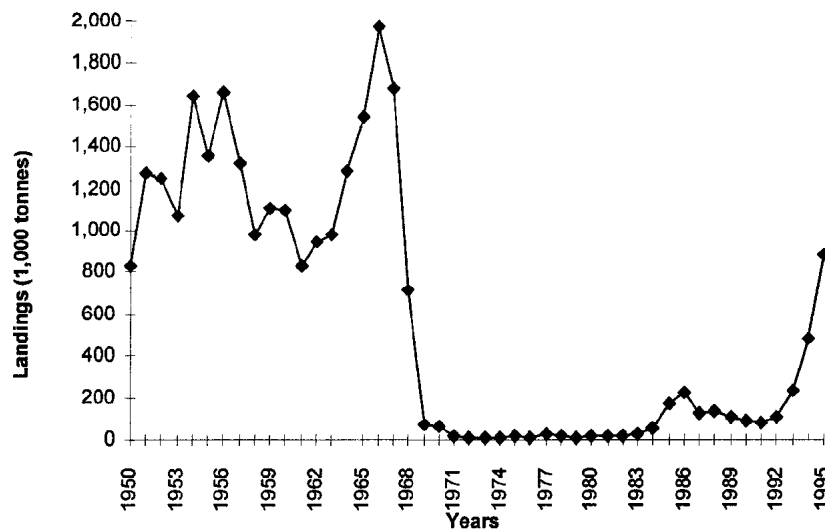
Figure 2. Landings of NSSH in the Period 1950–95
Source: Bjørndal *et al.* (1998).

Russia, and the EU. The migration pattern for the NSSH consists of four phases. Migration begins in the spawning area, proceeds to the maturing area for juveniles, and then to the feeding area. It 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 for management of the straddling nature of the stock are analysed in a game theoretic context by Bjørndal *et al.* (2004).

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 into 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).

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 dynamics model will be constructed using the Beverton-Holt population dynamics 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 (Sumaila 1997), or the recruitment of exceptionally good year classes, has been noted (Hannesson 1975). The choice of this model for analysis of the NSSH fishery is not arbitrary because this stock is long-lived, consisting of many cohorts, and is unusual since it has 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 $t - i + \underline{s}$, $R_{t-i+\underline{s}}$, where $\underline{s}$ is the age of recruitment and the total mortality of the fish composed of the fishing mortality, $F_{i,t}$, and natural mortality, $M_{i,t}$:

$$N_{i,t} = R_{t-i+\underline{s}} \; \exp \left[- \sum_{j=\underline{s}}^{i-1} (F_{j,t-i+j} + M_{j,t-i+j}) \right] . \tag{1}$$

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

$$B_t = \sum_i p_{i,t} N_{i,t} \bar{w}_{si,t}, \tag{2}$$

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

$$Y_t = \sum_i C_{i,t} \bar{w}_{i,t}, \tag{3}$$

where catch is given by:

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

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 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.

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 is $M = 0.12$ for ages three onward, 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 (1998) lead to the conclusion that the value of $M = 0.13$ is appropriate for recent years, since there appears to be no justification for the assumption of additional disease-induced mortality.

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 juveniles of the NSSH are on the order of 1.56 at age 1 to 0.54 at age 2 (Barros 1995).

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).

A Bioeconomic Model for NSSH

The model of population dynamics will now be simulated for the period of 1986–95, and the results will be compared with actual data in order to evaluate model performance. 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. 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 catches, all taken from Patterson (1998), except $M_{i,t}$ and $F_{i,t}$. Recruitments for 1986–95 are values found in Patterson 1998 (Table C4). Data on weights at catch and spawning and maturity are obtained from historical stock data. 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 with the actual values observed, but is always lower. Thus, the agreement is more qualitative than quantitative. From figure 4, it can be seen that the model tracks the observed landings very well, except for the initial year. The simulated values are somewhat higher between 1986–90, almost equal to actual values between 1991–93, while they are lower in 1994 and 1995.
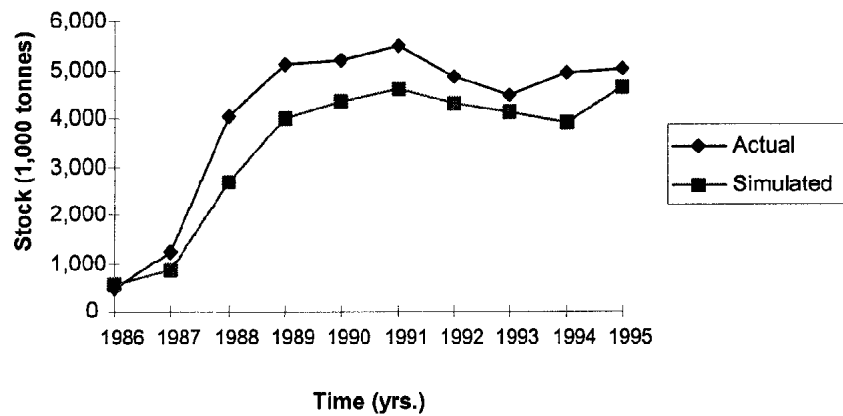
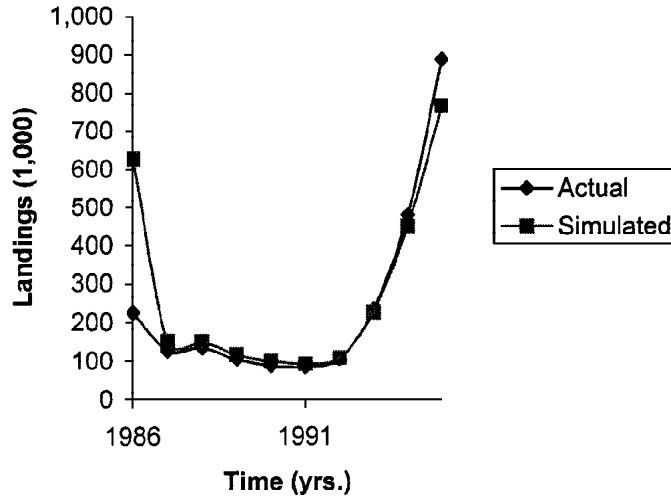**Figure 3.** Actual and Simulated Spawning Stock (1986–95)

Figure 4. Actual Landings and Simulated Yield 1986–95

An Optimization Model for the NHHS

We now combine the model of population dynamics with an economic model. We 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 preset time horizon. For this analysis, the price of fish per unit and harvesting costs are assumed to be constant. Given these assumptions, the annual profits are given by:

$$\Pi_t = (p - c)Y_t, \tag{5}$$

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:

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

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 that yields the maximum profits subject to the population dynamics of the model.

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

The justification for assuming a constant cost per unit harvested is what we are dealing with in 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 until the stock is virtually 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 NSSH fishery, where they found that cost was basically constant per unit harvested.

Data and Results

Due to the sensitivity of the recruitment function used in this study, the time horizon of the simulations is 20 years. 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
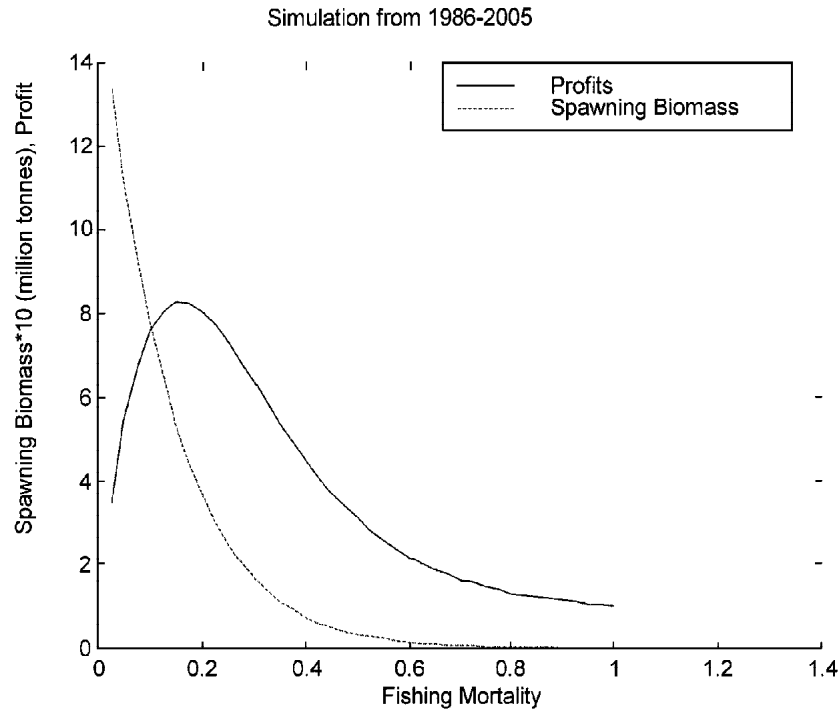
Figure 5. Discounted Profits (Billion NOK) and Total
Spawning Biomass for Different Fishing Mortalities
Note: * means biomass is multiplied by 10 as a multiplicative factor.

Simulation from 1986-2005
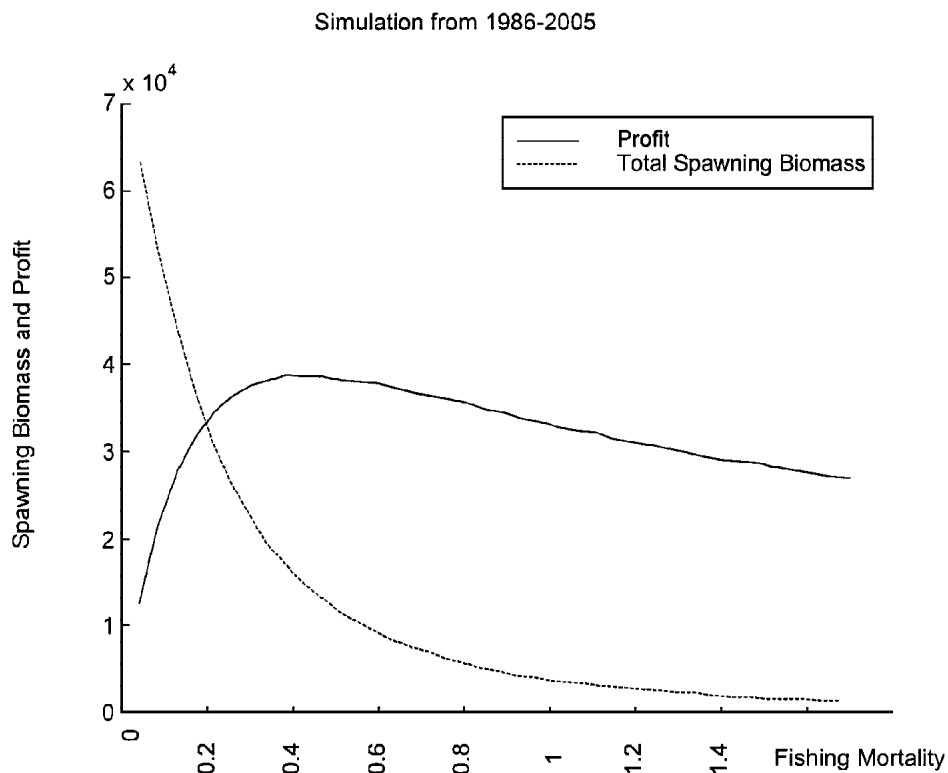
Figure 6. Simulated Profits (billion NOK) and Spawning Biomass (million tonnes) for Different F-Values. Actual Recruitment for 1986–96; Average Recruitment for 1993–96 used for 1997–2005 Period

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 0 and 0.4 and is reduced to almost 0 for $F = 0.8$.

When simulating the spawning biomass and the annual yield for the optimal fishing mortality ($F = 0.15$), both increase from 1986 onwards. 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 recruitment function form. Sensitivity analysis shows that using actual data for the SSB in Patterson (1998) 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 of 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 6). Available values from 1986–96 were used, while the mean value of 1993–96 was used for the remaining period since we do not have any observations. That is, for the years in which we have no observations, the mean value of the period 1993–96 was used, meaning a constant recruitment is assumed. The solid line in figure 6 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 gentler 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.

We have also undertaken a sensitivity analysis for changes in some of the biological parameters (table 2). In particular, the natural mortality rate (M) was set equal to 0.15 for all year classes. Moreover, there is no selectivity in the fishery. The optimal fishing mortality has been estimated for different simulation periods, all starting in 1986 (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 20 years (1986–2006). The lower optimal F-values, as compared to the initial cases investigated, can be explained by changes in the biological parameter 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

Conclusion

We have traced the historical development of the NSSH and shown that stock size can vary substantially over time. The spawning biomass of the NSSH ranged from 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, 2 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 was the case.

Focusing our attention on the high variability of the stock, we developed a model of population dynamics for the NSSH based on the Beverton-Holt age-structured model. Simulations of the biomass and landings 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 NSSH.

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

NSSH 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 required for the sustainable exploitation of the stock and in order to avoid a new stock collapse. For this reason, analyses of the management of a fishery such as this take on added significance.

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