



HAL
open science

Economic and biological risk analysis of the Norwegian spring-spawning herring fishery

Suzanne Touzeau, M. Lindroos, V. Kaitala, J. Ylikarjula

► **To cite this version:**

Suzanne Touzeau, M. Lindroos, V. Kaitala, J. Ylikarjula. Economic and biological risk analysis of the Norwegian spring-spawning herring fishery. *Annals of Operations Research*, 2000, 94 (1/4), pp.197-217. 10.1023/A:1018973217951 . hal-02921849

HAL Id: hal-02921849

<https://hal.science/hal-02921849>

Submitted on 23 Jan 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Economic and biological risk analysis of the Norwegian spring-spawning herring fishery*

S. Touzeau^a, M. Lindroos^{b,†}, V. Kaitala^{b,c} and J. Ylikarjula^b

^a*CSIC, ICM: Institute of Marine Sciences, Passeig Joan de Borbó s/n, E-08039 Barcelona, Spain*

^b*Systems Analysis Laboratory, Helsinki University of Technology, P.O.Box 1100, FIN-02015 HUT, Finland*

^c*University of Jyväskylä, Department of Biological and Environmental Science, P.O.Box 35, FIN-40351 Jyväskylä, Finland*

Abstract

The purpose of this paper is to study the biological and economic risks involved in the management of the Norwegian spring-spawning herring fishery. We use a discrete time and age-structured model based on historical data. The current paper investigates, under different levels of fishing mortalities, the risk probabilities related to the time behaviour of the spawning stock and profit. We show that the exploitation of the herring stock is vulnerable to small changes in harvesting and price level.

Keywords: fishing, Norwegian spring-spawning herring, population dynamics, risk analysis.

1. Introduction

The Norwegian spring-spawning herring (*Clupea harengus*) is potentially one of the largest and most valuable fish stocks in the world [4]. It is a pelagic stock which lives on plankton. Consequently, the herring has an important role as a transformer of the plankton production to higher trophic levels. As a common feature of a pelagic fish the feeding of the herring stock is limited to a few months in spring and summer.

The Norwegian spring-spawning herring stock is also highly migratory in nature. The juvenile part of the stock generally resides in the Barents Sea. The mature part of the stock, after spawning off the Norwegian west coast, undertakes extensive feeding migrations. When the spawning stock is large enough these migrations take it across the North Atlantic to the areas north and east of Iceland. On the way the herring stock crosses also the Faeroes fisheries jurisdiction and a high seas area called the Ocean Loop [4].

*This paper is a part of the FAIR Project PL 96.1778 “The Management of High Seas Fisheries”, funded by the European Commission. This document does not necessarily reflect the views of the Commission of the European Communities and in no case anticipates the Commission’s position in this domain. We acknowledge valuable comments from Trond Bjørndal, Daniel Gordon, the anonymous referee and participants of the Project. We also thank Tuomas Raivio for helping to create the 3D figures.

[†]Corresponding author: Marko Lindroos, e-mail: marko.lindroos@hut.fi

The aim of this paper is to study the economic and biological vulnerability of the Norwegian spring-spawning herring fishery. Risk analyses are important and well-motivated in the herring fishery due to the past history of serious overexploitation. Moreover, the fisheries along the coast line of Norway have always been highly unstable, due to fluctuating recruitment and changing migratory patterns. However, here we do not take into account the seasonal and spatial aspects of the management of the stock, because we prefer having a simple model in order to capture the risk elements of the fishery more precisely. In the current paper, we analyse biological and economic risks caused by harvesting the stock. The uncertainty from which both risks arise concerns the recruitment process.

The risk analysis consists in studying whether some variables, e.g. the spawning stock biomass, will decrease below a certain critical value. We introduce two measurements of this risk concept. The first one is the probability of getting at least once below the critical level. The second risk measurement is the percentage of years that the variable stays below the specified level. We assess these risks and study the risk distributions of the herring model. The biological risk analysis is focused on studying probabilities of given harvesting policies for which the spawning-stock biomass is below a predefined safe minimum biological level given in [4]. Economic risk analysis studies, with varying prices, the probabilities of given harvesting policies for which profits are negative at some point of time. In addition, we study the percentage of years when the fishery is making losses.

Biological modelling and parameter estimation of the Norwegian spring-spawning herring stock dynamics have been completed by Patterson [11]. Actually, several alternative models have been identified, depending on the chosen stock-recruitment function and on whether density-dependent effects are taken into account or not. However, only one has been chosen for explicit presentation in this article: a discrete time, age-structured and density-independent model, with a Beverton–Holt stock-recruitment relationship. It constitutes the basis for the biological part of this study. However, previous analyses were performed on the different models (e.g. in [12]) and their results are sometimes referred to. The biological model has been coupled with a simple economic model: fixed fish price and a loglinear cost function.

The current paper is organized in the following way: Section 2 is a presentation of the bioeconomic model. Section 3 briefly describes the data available. Then in Section 4 we proceed to the risk analysis, the heart of this paper. Finally conclusions are drawn and perspectives for further research are proposed.

2. Bioeconomic model

The biological modelling has been developed in the FAIR-CT96-1778 Project [11], as well as the cost function on which the economic part is based [3]. Subsection 2.1 summarizes the main features of the model in order to understand the procedures described in the risk analysis section 4. Subsection 2.2 is a numerical equilibrium study.

2.1. Description of the model

This subsection is dedicated to the mathematical description of the bioeconomic model. The first parts 2.1.1 and 2.1.2 concern the biological model, whereas subsections 2.1.3

and 2.1.4 introduce harvest and profit. To ease the reading of the present paper, tables describing the values and units of the parameters are displayed. Table 1 summarizes most notations used hereunder.

Table 1: Notations.

| Subscripts | definition | Range | |
|-----------------|------------------------------------------------|-------------------------------------|------------|
| a | age | $\{0, 1, 2, \dots, 16\}$ years | |
| y | time | $\{y_1, \dots, y_2\}$ year interval | |
| Variables | definition | Unit | Subscripts |
| N | abundance | individuals | a, y |
| B | biomass | kg | a, y |
| SSB | spawning stock biomass | kg | y |
| R | recruitment | individuals | y |
| F | fishing mortality | none | y |
| C | catch | individuals | a, y |
| Y | yield, total catch in weight | kg | y |
| Q | costs | NOK | y |
| P | profit | NOK | y |
| ε | stochastic variable | none | y |
| Parameters | definition | Value & unit | |
| m_a | natural mortality | <i>cf. table 2</i> | |
| a, b, σ | stock-recruitment parameters | " | |
| CW_a | individual weight at age in the catch | <i>cf. table 4</i> | |
| SW_a | individual weight at age in the stock | " | |
| MO_a | maturity ogive (rate) | " | |
| a_1 | first fishing age | <i>cf. table 3</i> | |
| S_a | selectivity | " | |
| h | fish price per kg | " | |
| q_1, q_2, q_3 | cost parameters | " | |
| Y_v | average harvest of a single purse seine vessel | " | |

2.1.1. Population dynamics

We consider a population dynamics model, known in the fisheries literature as the Ricker model. It is a discrete time and age-structured model:

$$\begin{aligned}
 N_{0,y} &= R_y & y > y_1 \\
 N_{a+1,y+1} &= N_{a,y} e^{-m_a - S_a F_y} & a \in \{0, 1, \dots, 15\} \\
 N_{a,y_1} &\text{ known} & a \in \{0, 1, \dots, 16\}.
 \end{aligned} \tag{1}$$

The population is represented through 17 age classes, from age 0 to age 16. Parameter y_1 is the initial year, for which we assume that all abundances at age N_{a,y_1} are known (cf. section 3). Usually, only the harvested fraction of the population is considered, i.e.

the stock (mainly because most data available concern the stock). However, here all development stages are included.

To calculate the flow into the first age class (0), a stock-recruitment relationship is used (cf. section 2.1.2), linking the number of recruits R to the spawning stock biomass SSB . Recruits are usually juveniles entering the exploitable phase, but in this model they rather correspond to viable eggs or larvae. Thus, this relation should better be considered as a *spawning function*.

All age classes are submitted to *natural mortality* (constant rate $m_a = 0.15$ for mature fish and a higher juvenile mortality) and possibly to harvest. The latter is introduced by the means of a fishing mortality term F_y , related to the effort applied to the stock each year, and a selectivity rate S_a , that describes the vulnerability of each age class (see the more thorough discussion in section 2.1.3).

In order to describe the population growth we need to express the *individual weights at age*. These values derive from historical data and are estimated separately from stock and catch samples (cf. section 3). Therefore we obtain two sets of parameters: the stock weights at age SW_a and the catch weights at age CW_a , that are slightly different. Parameter CW is needed for the catch in weight defined in section 2.1.3 and SW enables to express the *population biomass* in year y :

$$B_y = \sum_{a=0}^{a=16} B_{a,y} = \sum_{a=0}^{a=16} SW_a N_{a,y}.$$

2.1.2. Recruitment

The ageing of the population is described in equation (1), but to close the loop it is necessary to link the recruits to the spawners. For this purpose Beverton–Holt’s stock-recruitment relationship, very classical in the fishery field [6, 8], is used. It assumes there is food limitation and competition among the juveniles [2]. Furthermore, to take into account the variability of the recruitment, a stochastic error term is added to this deterministic function. First, however, the spawning stock needs to be estimated.

The maturity ogive MO_a , defined as the proportion of mature individuals among age class a , characterizes the spawning level. It is assumed that the older part of the population (from age class 7) is fully mature, whereas the younger one (until age class 3) does not spawn. The intermediate age classes are partially mature. To assess the maturity ogives of the intermediate classes, we refer to historical data (cf. section 3). The *spawning stock biomass* is then given by:

$$SSB_y = \sum_{a=0}^{a=16} MO_a SW_a N_{a,y}. \quad (2)$$

Beverton–Holt’s *recruitment*, to which a log-normal error term is added, is the following:

$$R_y = \frac{aSSB_y}{1 + SSB_y/b} e^{\varepsilon_y}. \quad (3)$$

The error term reflects the high variability in recruitment due to numerous external factors (e.g. cod predation, environmental fluctuations). Random variable ε_y is normally distributed with mean 0 and variance σ .

The parameters of this stock-recruitment relationship as well as the natural mortalities are shown in table 2.

Table 2: Herring stock parameters, estimated in [11].

| Parameter | Value | Unit |
|-------------------|----------|--------------------|
| Mortality | | |
| $m_{0,1,2}$ | 0.9 | none |
| $m_{3,\dots,16}$ | 0.15 | none |
| Stock-recruitment | | |
| a | 32.459 | kg ⁻¹ |
| b | 3044.867 | 10 ⁶ kg |
| σ | 1.763 | none |

2.1.3. Catch

From a given cohort (a cohort is constituted of the fish born the same year), if we consider the fish that have disappeared during year y and take the proportion that died of harvesting, we obtain the following catch in numbers:

$$C_{a,y} = \frac{S_a F_y}{m_a + S_a F_y} (N_{a,y} - N_{a+1,y+1}).$$

Then, knowing the weights at age, we only need to sum these catches over all cohorts to obtain the total catch in weight, or *yield*. Combined with equation (1), its expression is the following:

$$Y_y = \sum_{a=0}^{a=16} Y_{a,y} = \sum_{a=0}^{a=16} CW_a N_{a,y} \frac{S_a F_y}{m_a + S_a F_y} (1 - e^{-m_a - S_a F_y}). \quad (4)$$

As mentioned in section 2.1.1, the harvest is the result of fishing mortality F_y and selectivity S_a included in the population dynamics. The *fishing mortality* is related to the effort applied by fishermen on the stock and is considered as a control term. Referring to the data (cf. section 3), a realistic range for the fishing mortality would be: $F_y \in [0, 2]$, 0.35 being a mean value over the recent years.

The *selectivity* depends on the interaction between fish and gear; all age classes are not as vulnerable and each gear is more or less efficient towards the age classes. A simple *selection pattern* has been chosen here. It consists in cutting the age classes into two groups: age classes that are not yet harvested because they are below the first fishing age a_1 and age classes that are harvested. The respective selectivities for these two groups are: $S_a = 0$ ($a < a_1$) and $S_a = 1$ ($a \geq a_1$). The first fishing age a_1 is generally 3.

Another possibility would be to use historical data for assessing the selectivities. Even with a more detailed selection pattern the hypothesis of separation between selectivity

and fishing mortality may be too simple. For control purposes, it should be possible to modify the selectivity to reflect a change in the fishing gear. However, for the risk analysis presented in section 4, this selection pattern seems adequate.

2.1.4. Economic yield

To the biological model described above, we add a very simple economic model. The fish price per kilogram h is assumed to be constant. The harvesting costs for each vessel are composed of a log-linear cost function (see [3] for estimation procedures). The cost function has been estimated with mean level of input prices, vessel size and catch level of other fish.

Table 3 compiles the harvesting and economic parameters. The cost parameters have been estimated for an average vessel of the Norwegian purse seine fleet. Parameter Y_v is the average catch of a single vessel and it is used as a scaling parameter in the cost function. In order to obtain an estimate for the costs of the whole fishery we assume that the Norwegian spring-spawning herring fishery is composed of 100 identical vessels (during the last few years the Norwegian purse seine fleet has consisted of about 40 vessels possessing one third of the total herring quota) described by the cost function for the Norwegian purse seiners. So the *costs* in year y are:

$$Q_y = 100 q_1 \left(\frac{Y_y}{100 Y_v} \right)^{q_2}.$$

Having the cost function defined in this way is of course incorrect since there are also other vessel types in the fishery. But since other countries such as Iceland also have quite similar purse seine vessels the mistake that we make is probably not too large. In addition, changing the variables or the functional form of the cost function might change our results, but since the cost parameters were estimated using data described in [3] the results that we obtain are not too far from the “true values” in this respect. A further limitation concerns the range for which the cost function is appropriately defined. For very low or very high levels of harvesting the cost function gives imprecise values. Thus, at extreme points we are uncertain whether the profits that our model gives are accurate.

Furthermore, we assume that the harvesting costs also depend on the spawning stock biomass level. If, for given fishing mortality and simulation, the mean spawning stock biomass over the simulation time period is smaller than the critical level SSB_{crit} , the fishing fleet is given a penalty worth q_3 : directly as a fine, or indirectly as the consequence of possible negative economic effects. For example, if a fishing moratorium exists, commercializing the fish might be more expensive. The q_3 value (cf. table 3) is hypothetical only, but since our cost function is specified for a given range of fishing mortalities only, we use it as a means to extend the range for higher F's. The effect of the penalty on the results is not very large, but we do think adding it is appropriate.

Thus, the *annual profit* function we use throughout the paper is:

$$P_y = hY_y - 100 q_1 \left(\frac{Y_y}{100 Y_v} \right)^{q_2} - \begin{cases} q_3 & \text{if } SSB_y < SSB_{crit} \\ 0 & \text{else.} \end{cases} \quad (5)$$

Table 3: Harvesting and economic [3] parameters.

| Parameter | Value | Unit |
|------------------|--------|-------------------------------|
| a_1 | 3 | year |
| $S_{0,1,2}$ | 0 | none |
| $S_{3,\dots,16}$ | 1 | none |
| q_1 | 3.4184 | 10^6 Norwegian kroner (NOK) |
| q_2 | 0.56 | none |
| q_3 | 100 | 10^6 NOK |
| h | 1.45* | NOK/kg |
| Y_v | 1.2449 | 10^6 kg |

* 1995 mean value taken from Norges Sildesalgslag: Årsmelding, vol. 1989-1995.

2.2. Equilibrium study

Simulations have been performed to look into the *equilibrium characteristics* of the model. For this aim, we use a modified version of the stock-recruitment relation where the stochastic term is replaced by the expected value of the recruitment function. The Beverton–Holt relation (3) is then given by:

$$R_y = \frac{aSSB_y}{1 + SSB_y/b} e^{\sigma/2},$$

where σ is the variance of the residuals obtained after the fitting of the stock-recruitment relation. The form of the corrective term $e^{\sigma/2}$ derives from the assumption of a log-normal error [8]. A further requirement, in order to reach the steady state, is to have a “long enough” simulation period: in this Section we use a simulation period of 60 years.

The stock dynamics simulations are run for a set of constant fishing mortalities, which ranges from 0 to 2. We observe the convergence of all variables towards fixed values, that vary depending on the fishing mortality level. Therefore, those end values are good approximations of the equilibrium state.

We are particularly interested in the spawning stock biomass (2) and the yield (4). Both steady state variables are represented along the fishing mortality (cf. figure 1). The equilibrium yield plot is of particular interest, because it shows the *Maximum Sustainable Yield* (MSY), a reference value in fishery management. We have also added a plot for equilibrium profit level. We notice that there is also a *Maximum Sustainable Profit* (MSP) for the fishery. In addition, we see that for high levels of fishing mortality the profit starts increasing again towards $-q_3$, since the harvest and the spawning stock are then very close to zero.

We are also interested in observing the influence of the selection pattern on the equilibrium profit. We therefore vary the first fishing age a_1 . Results are exposed in figure 2.

We notice that raising the first fishing age a_1 increases the *MSP* and then makes it disappear. From $a_1 = 8$, the profit does not decrease for higher fishing mortalities but increases slowly, probably towards a bounded value. At this point, the population survives through its younger classes, of which some are spawning, whereas the bigger fish are heavily

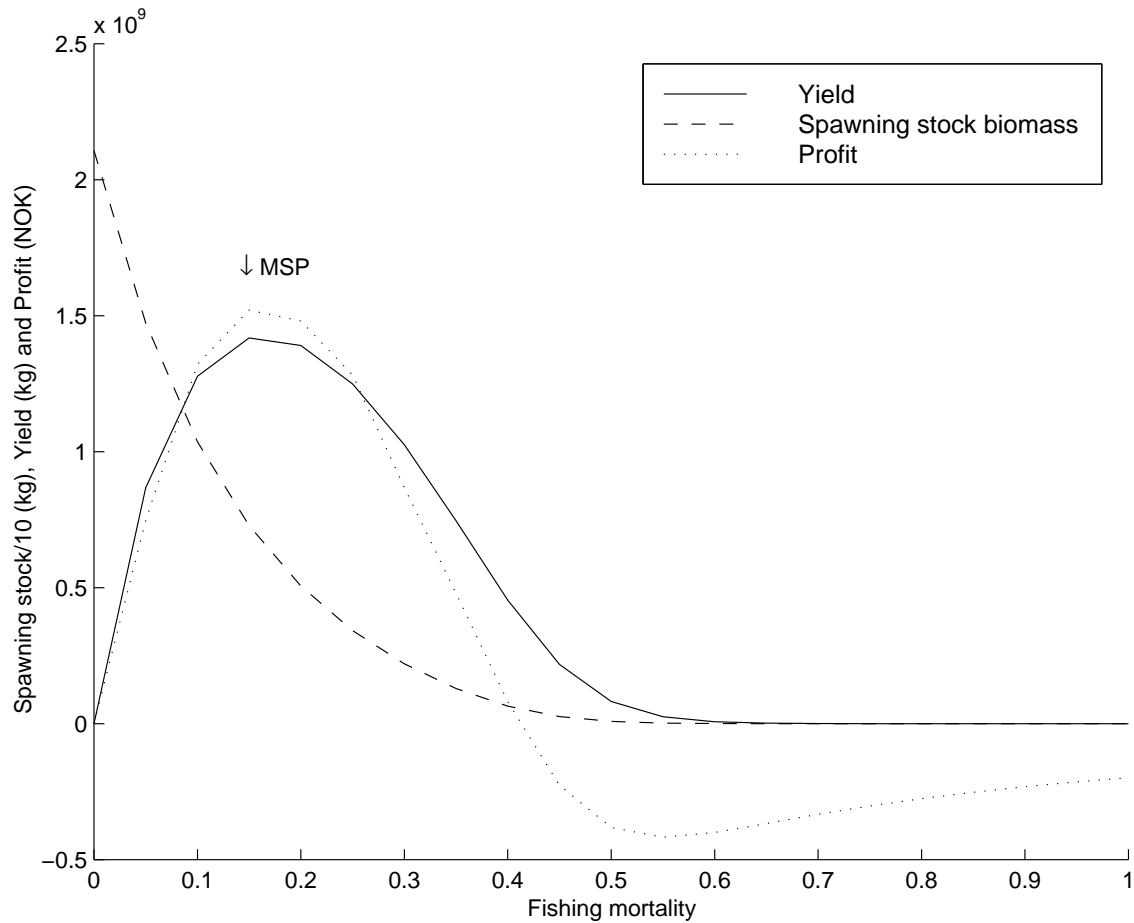


Figure 1: Equilibrium characteristics of the bioeconomic model.

harvested: a survival “niche” has been created. The penalty of the cost function can be seen as a slight kink in the curves when the harvesting becomes so intense that in equilibrium the spawning stock biomass falls below the safe biological level.

3. Data

Historical data concerning the herring population consist of age and year specific values, for each of the 17 age classes, sampled from 1950 to 1996. The data years are denoted as y' to distinguish them from the simulation years y . These data are available for the following variables: the abundances $N_{a,y'}$, used for computing the initial condition of equation (1); the maturity ogives $MO_{a,y'}$ as well as the the stock $SW_{a,y'}$ and catch $CW_{a,y'}$ weights at age, used in the density-independent model presented in section 2.1.1; the “fishing mortalities” $F_{a,y'}$ (including the selectivity factor), that could be used after rescaling to define historical selection patterns, more detailed than the one proposed in section 2.1.3.

The maturity ogives, stock and catch weights at age are conventional stock assessment data estimated by ICES from commercial catch observation [1]; they can also be found in

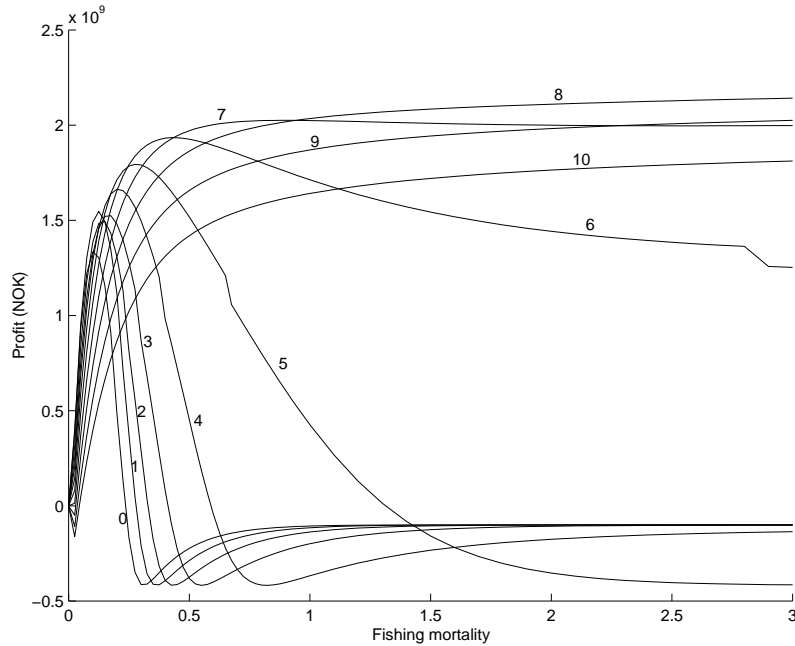


Figure 2: Influence of the selection pattern (1st fishing age = 0,1,...,10) on equilibrium profits.

appendix A of Patterson’s report [11]. The abundances and fishing mortalities have been estimated using a Bayesian approach presented in appendix B of Patterson’s report; the resulting data are shown in appendix C of the same report.

To estimate the catch weights at age, for instance, we could take the latest data available. However, to smooth the errors attached to the data, it would be preferable to use the CW_a mean value over a certain historical period. So if data years y'_1 to y'_2 are chosen, the following values will be used in the simulations:

$$CW_a = \frac{1}{y'_2 - y'_1 + 1} \sum_{y'=y'_1}^{y'_2} CW_{a,y'}.$$

The same procedure is used to compute the initial abundances, the maturity ogives and the stock weights at age. The data period chosen in this paper is [1993, 1996] and the resulting parameters are presented in table 4.

4. Risk analysis

The risk analysis consists in determining what risk there is, for a certain yearly variable X_y , to decrease under a critical value X_{crit} . Risk variables of particular interest are the spawning stock biomass SSB_y defined in equation (2) and the annual profit P_y defined in (5). The former is a good indicator of the biological risk, presented in subsection 4.2, because it represents the reproduction capacity of the stock; whereas the latter clearly

Table 4: Data parameters, estimated as mean values over data years {1993, . . . , 1996}.

| Age class a | MO_a (no unit) | SW_a (kg/individ.) | CW_a (kg/individ.) |
|---------------|------------------|----------------------|----------------------|
| 0 | 0 | 0.001 | 0.007 |
| 1 | 0 | 0.0135 | 0.0548 |
| 2 | 0 | 0.025 | 0.1085 |
| 3 | 0.005 | 0.0745 | 0.159 |
| 4 | 0.155 | 0.152 | 0.2105 |
| 5 | 0.7125 | 0.2343 | 0.2508 |
| 6 | 1 | 0.2995 | 0.2955 |
| 7 | 1 | 0.3468 | 0.3237 |
| 8 | 1 | 0.3598 | 0.352 |
| 9 | 1 | 0.3825 | 0.3668 |
| 10 | 1 | 0.3875 | 0.376 |
| 11 | 1 | 0.4017 | 0.3718 |
| 12 | 1 | 0.4037 | 0.386 |
| 13 | 1 | 0.3945 | 0.39 |
| 14 | 1 | 0.4053 | 0.395 |
| 15 | 1 | 0.4033 | 0.3967 |
| 16 | 1 | 0.4138 | 0.3975 |

depicts the economic risk, to which subsection 4.3 is dedicated. The risk is calculated for different fishing levels and we also study how changes in the price level affect the economic risk. But first, the risk assessment method is described.

4.1. Risk assessment method

For this study, a set of fixed fishing mortalities F is needed. For each fishing mortality, SIM simulations are performed over the same time period $[y_1, y_2]$. As we deal with risk, we keep the stochastic term on the stock-recruitment relationship and the simulation period is rather long (100 years). Furthermore, the number of simulations (SIM) is quite high, so as to approximate, for each F , the *risk probability* with the ratio of “risky simulations”.

Risk definition *A simulation is said to be risky in regard to a certain risk variable X , if there is at least one year over the simulation period, where this variable decreases below the associated threshold or critical value X_{crit} .*

So if there are for example 100 simulations and 5 of them are risky in the sense specified above, then the risk probability is close to 5%.

However, there are also other ways to assess risk. Hilborn & Walters [8] give one of the most common risk indicators as follows: “what percentage of years the stock will be below some specified level”. Therefore, we also included this aspect in our study. Note that our method for assessing risk is by no means a very uncommon one and that the approach taken in this paper is considered by some authors as risk assessment only (see [7]), since we do not include any decision analysis part.

For each of the above mentioned risk variables and as functions of the fishing mortality, the following output is obtained: the proportion of risky simulations (approximation of the risk probability), the mean and standard deviation of the first year and the number of years below the critical level. They are represented in figure 3 for the spawning stock biomass, respectively as part a), b) and c) of the 2D plots. Note that an error-bar is attached to each estimated value in b) and c). This bar is used to illustrate the standard deviations of the estimated values (+/- from the mean value).

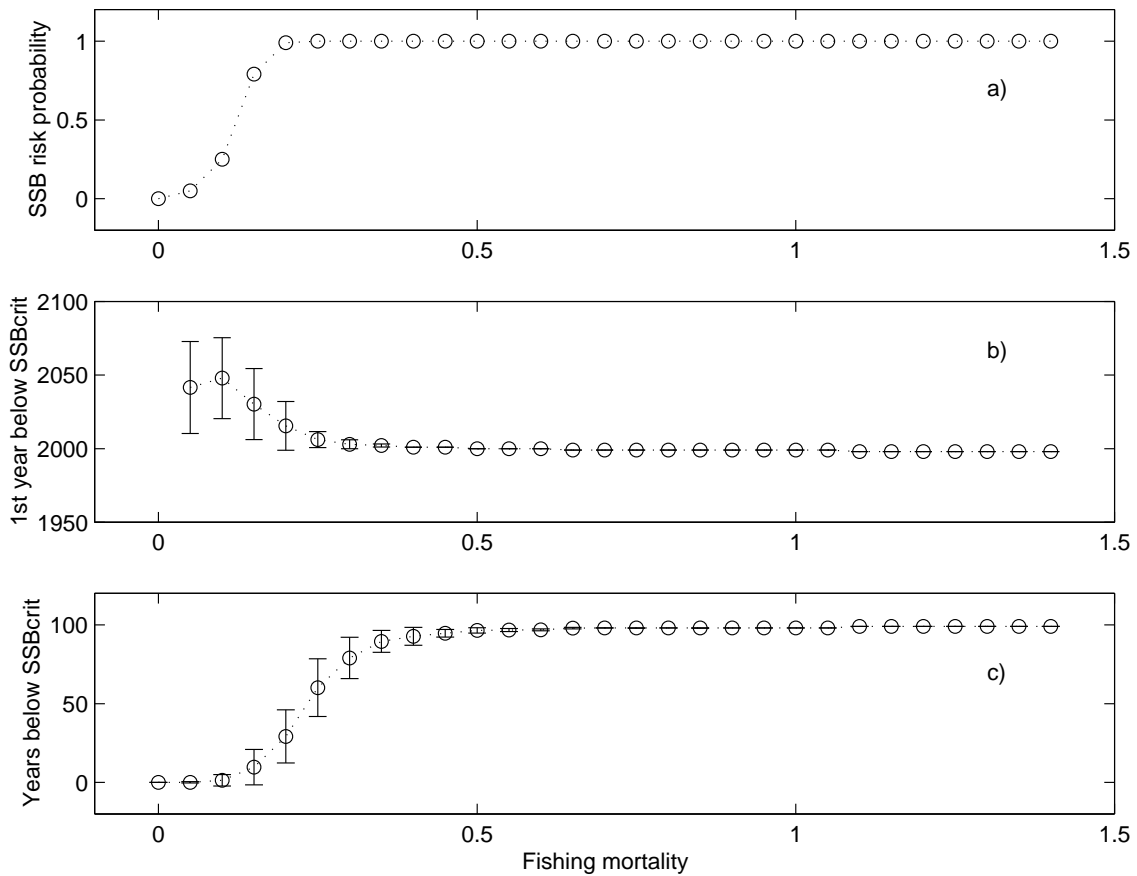


Figure 3: Biological risk.

Part b) shows the first year where the variable falls below its critical level. Combined with the number of years during which the risk variable is under the threshold, it gives an idea of the risk distribution. For $F = 0.2$, the first year below the limit for the spawning biomass occurs about 20 years after the beginning of the 100 years simulation period. However, only about 25% of this time is spent below the critical value, which means that the trespassing is probably only occasional. Part c) corresponds to the risk measurement according to Hilborn & Walters; it associates a degree of risk (negligible, medium, important, etc.), assessed by the number of years spent below the criteria, to the fishing mortality. For $F = 0.4$, the risk probability is almost equivalent to the $F = 0.2$ case in part a), but the proportion of years spent below the threshold as seen in c) is close

to 95%.

As a function of fishing mortalities F and simulation period, the mean value of the risk variable is also considered, in order to get a better understanding of the risk distribution. Figure 4 also visualizes the opportunities that the fisheries policymakers might have when choosing the level of fishing mortality. It can be thought of as a terrain where one has to travel by choosing the desired level of fishing mortality.

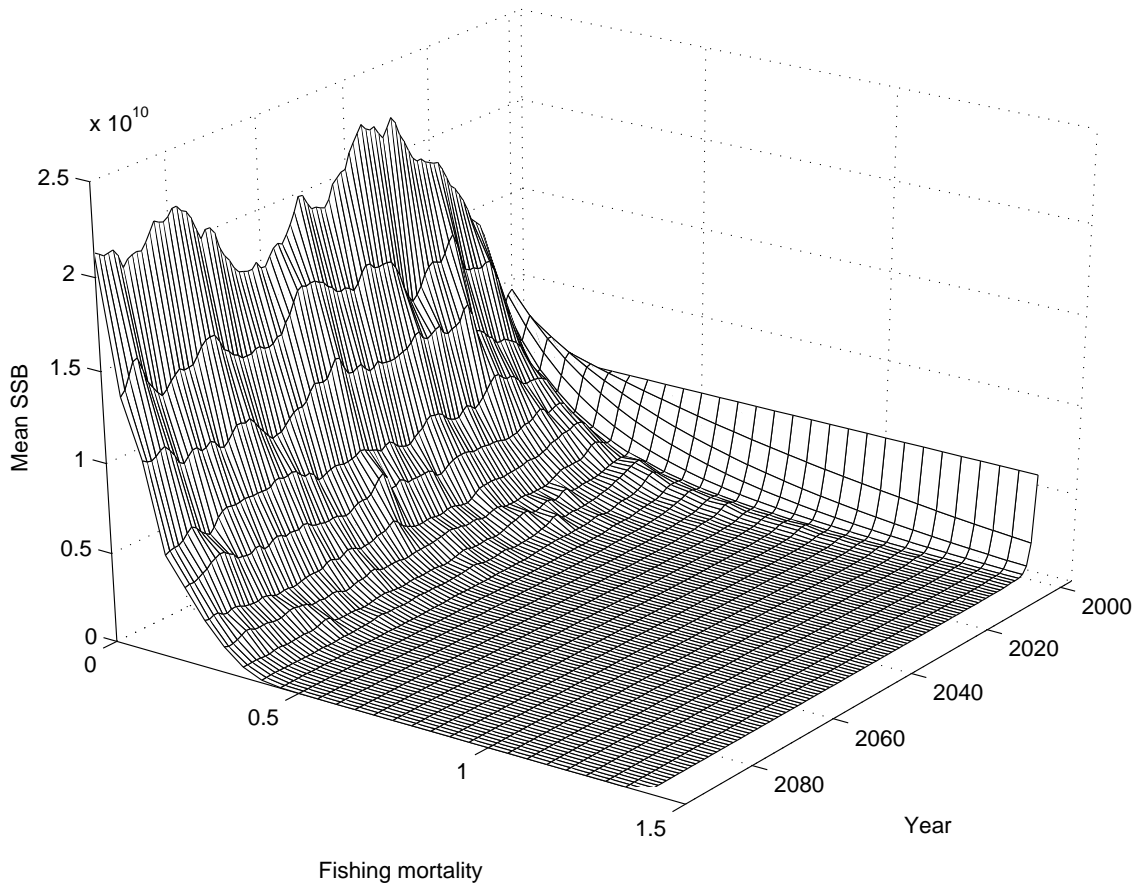


Figure 4: Biological risk distribution.

The risk analysis in the following sections has been completed using the parameters described in tables 2 and 3, as well as a set of constant fishing mortalities F that ranges from 0 to 1.4. The parameters and the critical values associated to the risk variables are given in table 5. The value SSB_{crit} was recommended in [4] and a zero profit assumption is commonly used in fisheries economics when considering for example an open-access fishery.

4.2. Biological risk

Figure 3 shows that the risk for spawning stock to decrease below its critical value increases rapidly almost from F equal to zero. The risk is already about 50% as F is slightly over

Table 5: Risk parameters.

| Parameters | Value(s) | Unit |
|--------------|--------------------------------------------------|------------------------|
| $[y_1, y_2]$ | [1997, 2096] | year |
| SIM | 100 | simulations |
| F | $\in [0, 1.4]$ | none |
| SSB_{crit} | 2.5 * | 10^9 kg |
| P_{crit} | 0 | Norwegian kroner (NOK) |
| h | $\in \{0.5, 0.9, 1.2, 1.45, 1.7, 2, 2.5, 4, 9\}$ | NOK/kg |

* Value chosen according to [4].

0.1. Thus, the biological vulnerability of the herring fishery increases with small changes in harvesting.

However, the mean number of years spent under the threshold becomes significant for higher fishing mortalities. Thus, in the sense of the alternative risk measurement, the percentage of years that the risk variable stays below the critical threshold, the 50% risk is achieved at a fishing mortality value of about 0.22. From $F = 0.4$ onwards, both risks are approximately 100%. We notice that the biological risk defined in figure 3c) shows less dramatic increase with more intense harvesting than the risk in 3a).

In what follows, we identify *three fishing zones*: the safe zone for fishing mortalities between 0 and 0.1, the totally unsafe zone for fishing mortalities higher than 0.4 and the intermediate zone, where there is a risk of falling below the threshold, but it can be reversed. Note that the standard deviations given by the error-bar are usually quite high in the intermediate zones.

For high fishing mortalities the total biomass and the spawning stock biomass are instantaneously driven beyond their critical value and remain below this level. We note here that the classification of risk probabilities depends on the risk tolerance of actual decision makers. This is especially important for the intermediate zone; the other fishing zones imply quite obvious decisions.

We would also like to point out that with higher values of a_1 , the first fishing age, the boundary values for the three fishing zones would also augment somewhat. Less age classes would be harvested, giving the stock a better chance to maintain itself above the critical value as the fishing mortality increases.

Figure 4 shows how the mean spawning stock biomass rapidly decreases until a quasi-extinction state as the fishing mortality increases. The spawning stock is very sensitive to the exploitation level, much more than to the stochastic variable which is introduced in the stock-recruitment function (3). As a conclusion we find that the herring population is very vulnerable to human harvesting.

4.3. Economic risk

This Section studies the economic risk of the herring fishery with a reference price of 1.45 NOK. The profits of the fishery are given in equation (5).

Figure 5 shows the mean risk, first year and the number of years below the yield critical

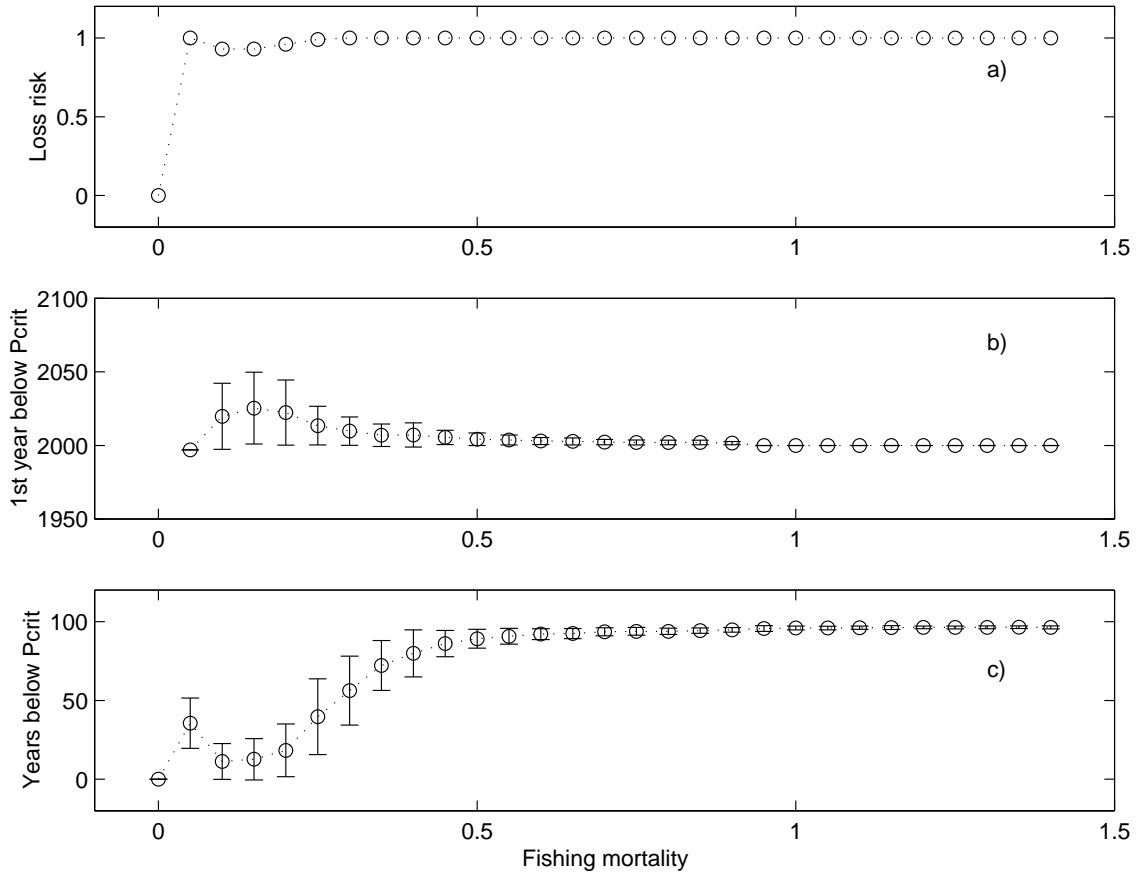


Figure 5: Economic risk.

value. We immediately see that we do not have a safe zone for the economic risk since there is always a positive probability that during the simulation period there is at least one year when the fishery is making losses. The intermediate zone is located approximately between $F = 0$ and $F = 0.5$. Raising fishing mortality higher than 0.5 means that it is very unlikely that profits will be achieved at all. Part c) of figure 5 shows that the number of loss years is smaller than profit years for $F = 0$ to $F = 0.25$. Furthermore, for $F = 0.1$ to $F = 0.2$ the number of loss years is quite small, only about 10-20 years and even zero loss years is within one standard deviation.

In figure 6, a peak region that remains more or less constant along time can be observed. It occurs for fishing mortalities around 0.15. It becomes even clearer as time goes by. So we can interpret this last plot as a stochastic version of figure 1, which represents the equilibrium profit, and compare this peak region with the MSP. The “stochastic MSP” (or sustainable path) is achieved for a similar fishing mortality, although it is lower than the actual MSP (0.2 in that case).

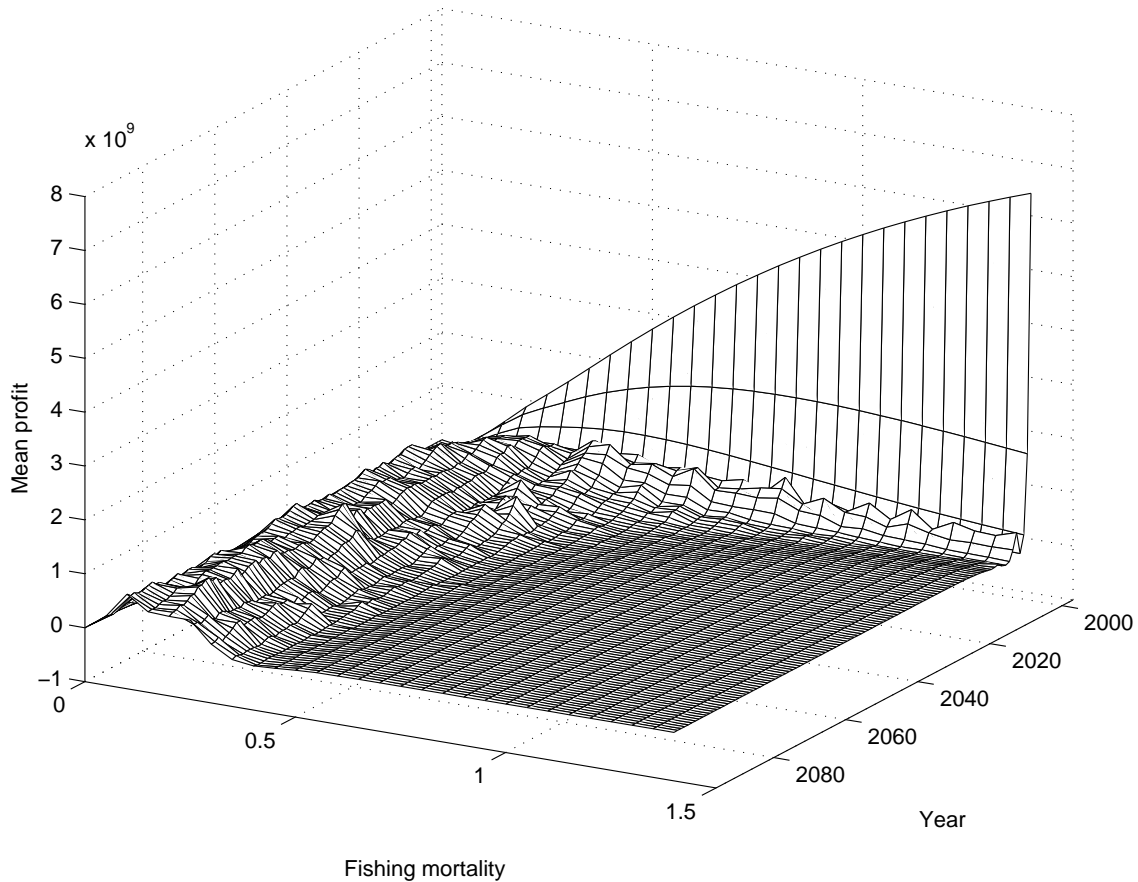


Figure 6: Economic risk distribution.

4.4. Price influence on the economic risk

In this section, we change the price level in order to see how sensitive the economic risk is to changes in economic conditions. The different prices h used are given in table 5. Figures 7 and 8 show the impact of the price level on the two risk measurements: the loss probability and the number of loss years. For both, the risk decreases when the price increases, which is logical as the revenues are greater.

At all price levels for high fishing mortalities, the loss probability is 1 because the stock is collapsing. For prices less than 2.5 NOK/kg, the loss probability is always positive. This means that the fishery will be making losses at some point in time, even at small fishing levels, because the revenues are not high enough. The number of loss years is also very important in the case of economic risk because it is the total profits that count in the long run. We observe that changing the reference price (1.45) slightly can have significant effects on economic risk. For example, in figure 7 with $F = 0.1$ raising price to 2 reduces loss risk from 0.9 to 0.2, approximately. Furthermore, in figure 8 we can see that with $F = 0.2$ lowering the price to 0.9 raises the number of loss years from 25 to 80.

We also see that even for very high prices the loss risk starts rising rapidly after $F = 0.3$.

For very high levels of fishing mortality the curves get closer to each other since positive profits can only be sustained for a few years initially, and after that profits remain negative for a long period. It should be noted that if prices are high it might seem tempting to harvest the herring stock heavily since, for example having $F = 0.4$ would only produce 10-30 years of losses out of 100. But even then we may well have a long period of negative profits which would be detrimental to the herring industry.

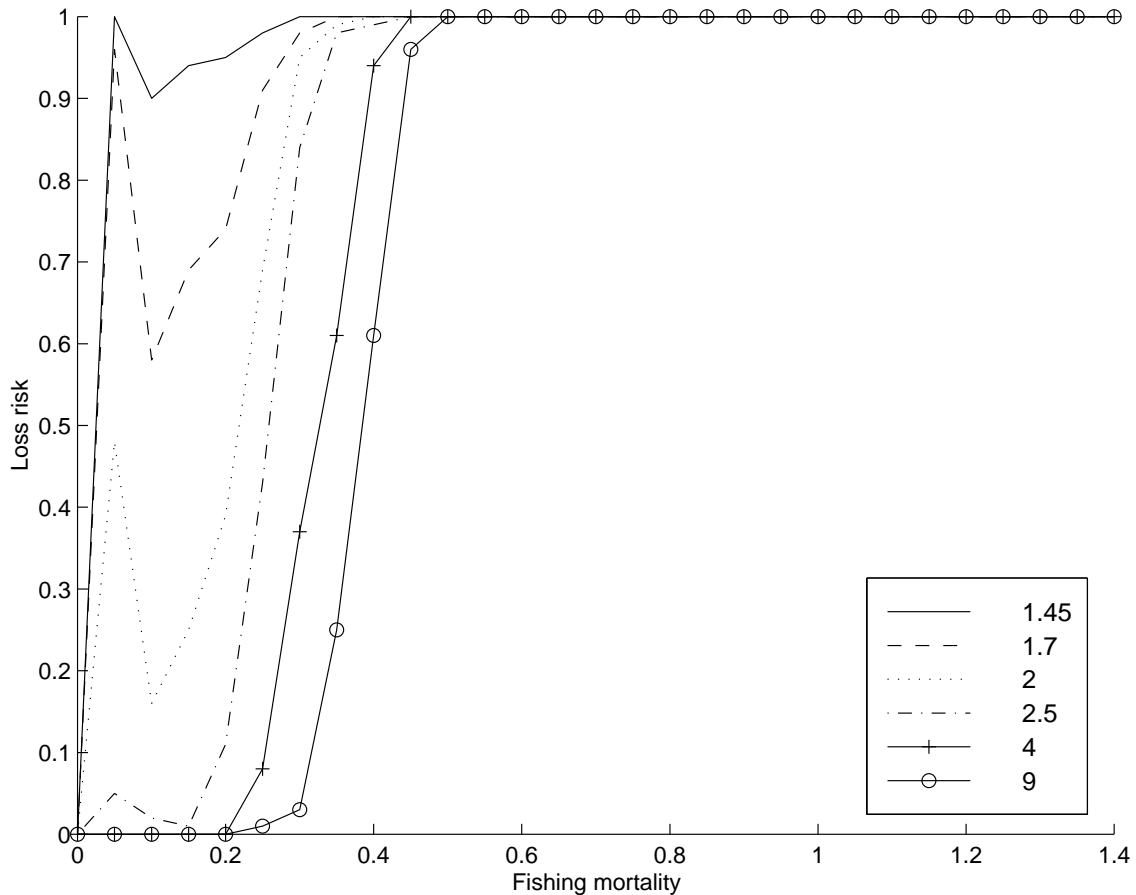


Figure 7: Sensitivity of the economic risk to changes in the herring price.

Figure 9 gives the critical fishing mortalities for which a given loss probability is reached, as a function of the price. Thus, for each price, we can define a fishing mortality interval in which the loss risk has given boundaries. E.g. for a price of 2 NOK/kg, the loss probability will be positive but lower than 50% for mortalities between 0.05 and 0.35. For a decision maker this kind of figure would be particularly useful since knowing the price of herring and risk one would be willing to take, we could immediately see the highest fishing mortality that could be used for harvesting. Then a TAC (Total Allowable Catch) could be set, taking into consideration the corresponding spawning stock biomass.

Finally, figure 10 gives the mean profits for various fishing efforts as the price increases. These are linear functions, because the harvesting level being set, the mean catch is a constant (cf. equation(5)). Fishing mortality value $F = 0.15$ always gives the highest

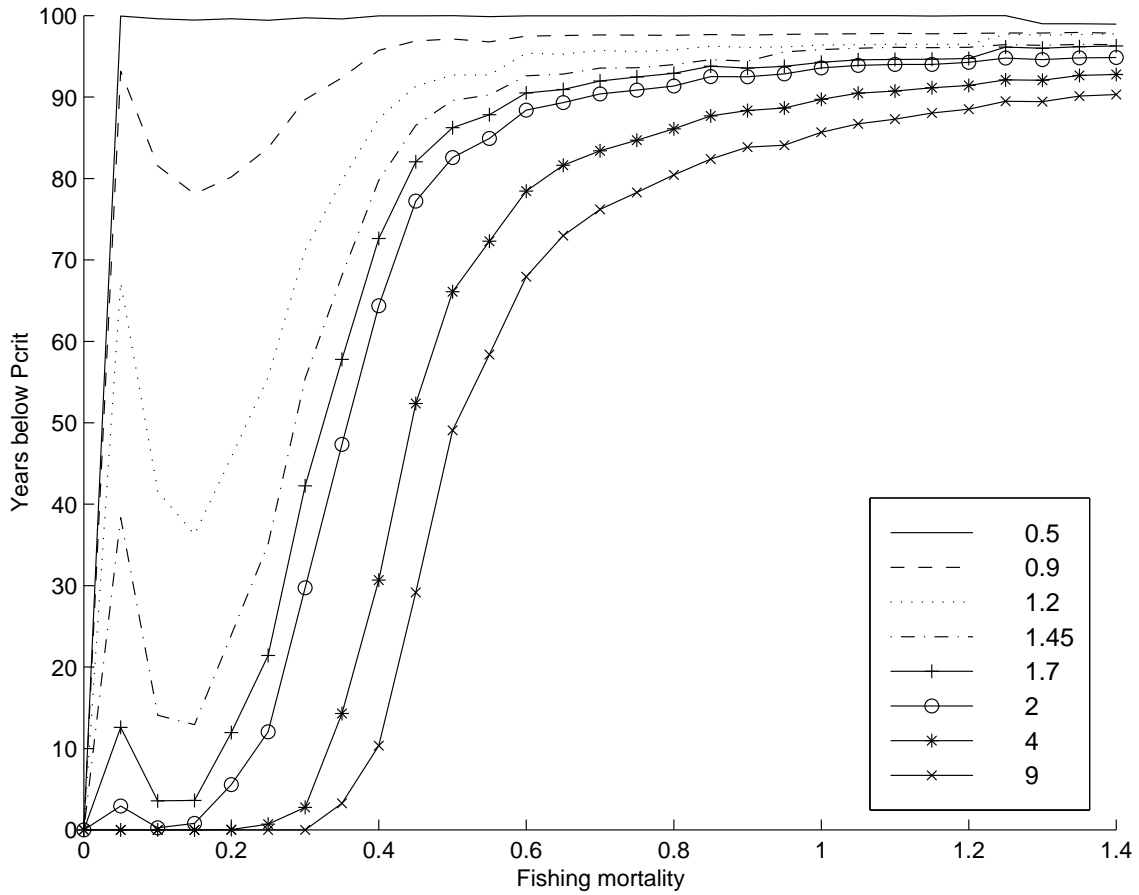


Figure 8: Sensitivity of the number of loss years to changes in the herring price.

mean profits. Thus, the “stochastic MSP” occurs independently of the price at this fishing level, but its value increases with the price. For the higher F value, we notice that the mean profit becomes only slightly positive as the price increases, due to overexploitation.

4.5. Discussion

Our risk analysis has revealed that the results may be sensitive to some modelling choices. Changing the stock-recruitment function and its stochastic variable (for example introducing autocorrelation), in other studies we have performed, has proven not to have any significant effects on the risk probabilities. However, introducing density-dependent functions instead of the data parameters of table 4 seems to increase the risks somewhat; this result is not very surprising as this last change also affects the equilibrium characteristic of the model [12].

Furthermore, the parameter sensitivity, not only for the price as in the previous section, should not be overlooked. In earlier analysis [12] we assumed the same natural mortality for all age classes ($m = 0.15$). The results of this paper, where we implement a higher juvenile mortality, differ quite radically from those that we previously obtained. The values

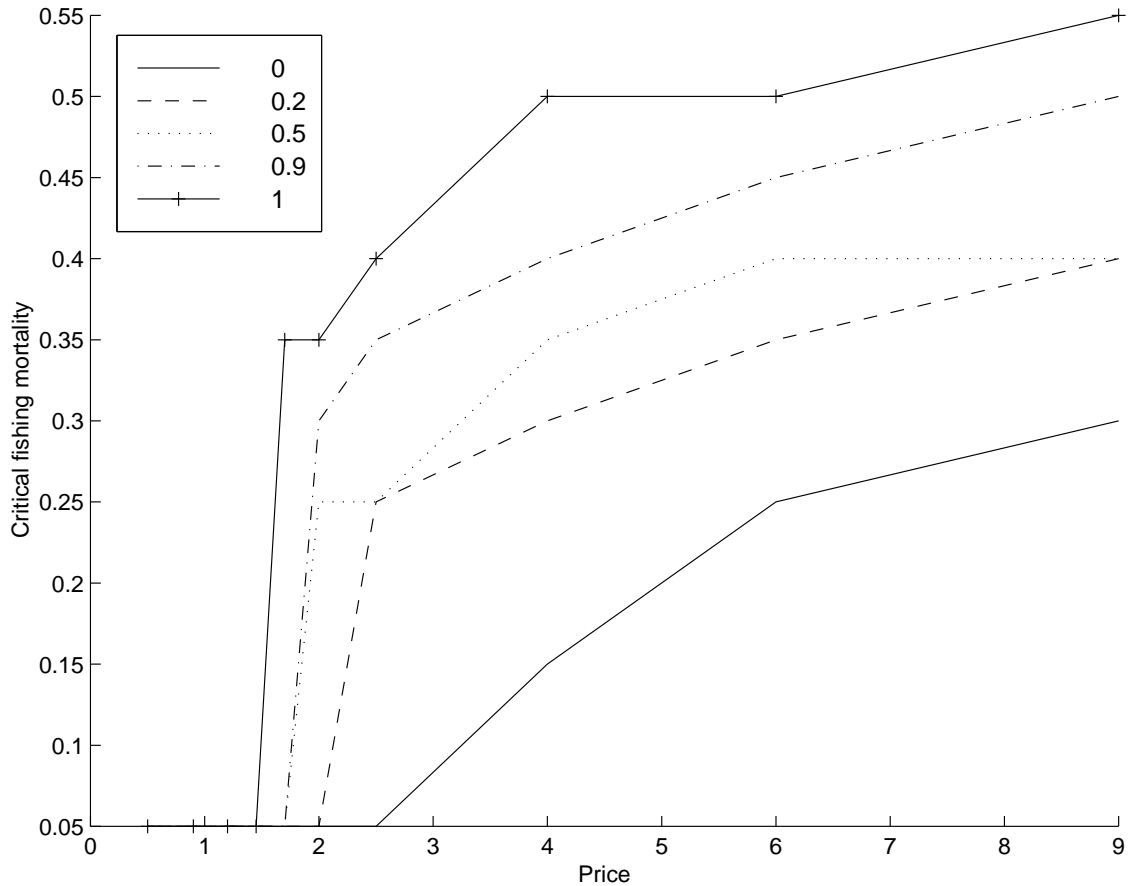


Figure 9: Influence of the price on critical fishing mortalities.

of stock, catch and profit are considerably lower at each level of fishing mortality and consequently, the risk probabilities are higher. Another critical assumption that especially affects the biological risk presented above (but also the economic risk) is the first fishing age a_1 . Increasing a_1 would decrease the risk. So maintaining the same effort level but augmenting the minimum landing size of the fish or recommending a change of gear (bigger mesh size) would reduce the biological risk, as it would leave more age classes unharmed by fishing.

In 1997 all the relevant countries, including the EU countries, have agreed on a maximum limit of catches for the Norwegian spring-spawning herring stock: 1.498.000 metric tons. In 1998 the countries agreed to continue cooperation, the total TAC (Total Allowable Catch) was set a bit lower than in 1997: 1.302.000 metric tons [5]. TACs of this magnitude are, according to our model, not sustainable in the long run even if we would increase the first fishing age substantially (to create a niche). However, in the short run the 1998 TAC can be sustained for 3 to 5 years if the harvesting level is high enough, depending on the first fishing age (e.g. $F > 0.3$ for $a_1 = 5$). Note that our risk assessment requires fixed fishing mortalities for the whole simulation period. In reality, the decision makers usually change their harvesting policy (TAC) annually, hence the mortalities may vary. Neverthe-

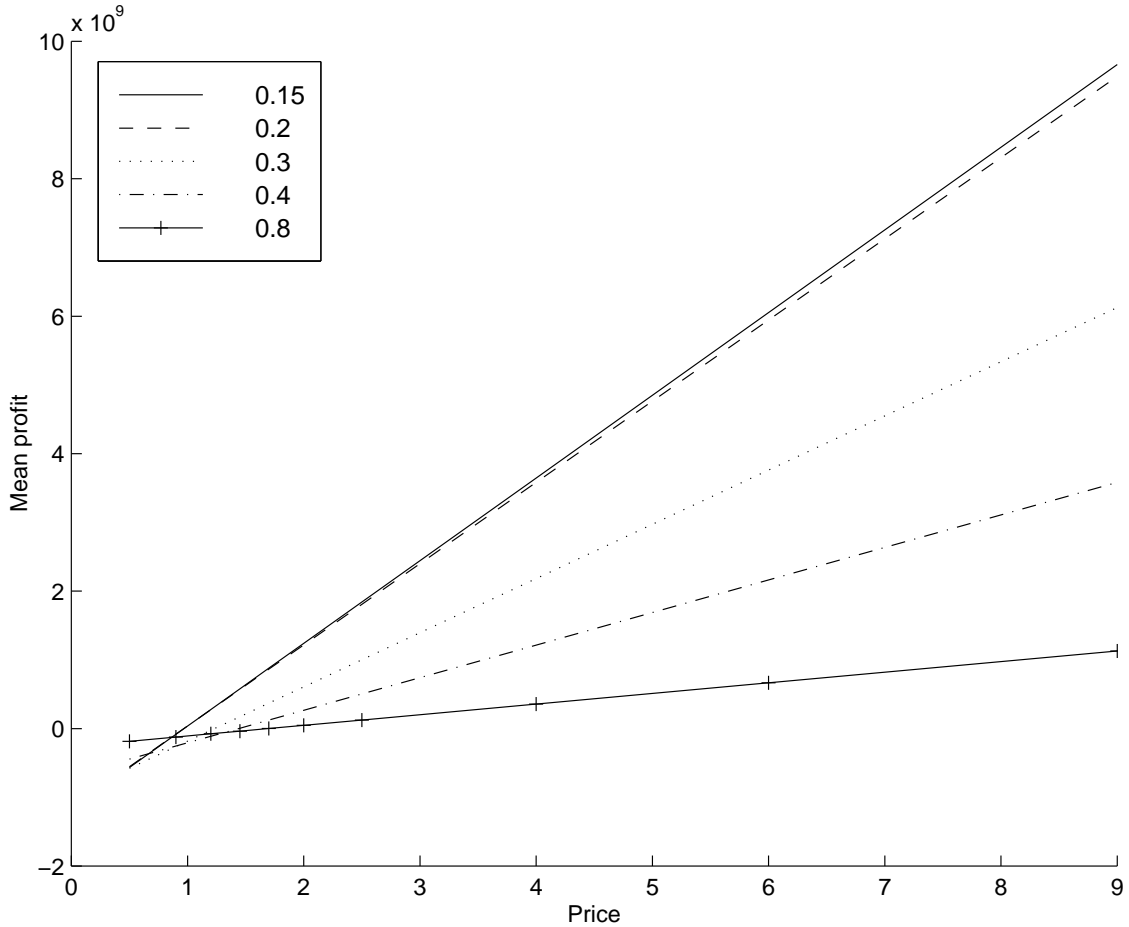


Figure 10: Mean profit as a function of price.

less, our study does not aim at simulating the fleet's behaviour, but provides information on the fishing limits, according to given criteria. Thus, a detailed analysis of TAC policies is left for future research.

5. Conclusion and perspectives

We have analysed a biological model of the Norwegian spring-spawning herring population dynamics coupled with a simple economic model. We have focused on biological and economic risk analysis for this stock.

Our risk analysis shows that the herring fishery is highly vulnerable to small changes in price and harvesting levels. We have also shown how the profits available from the fishery are strongly affected by the harvesting policy especially in the long run. Therefore, the effect of harvesting on the variability of the stock and the prevailing economic conditions should be carefully taken into account in the management of the stock.

We have shown the existence of a stochastic equivalent to the MSY, for around $F=0.15$

the yield and consequently the mean profit level is maximized (MSP). This harvesting policy recommendation would probably be slightly changed if we would apply discounting on the fishery's profits.

In addition, we have illustrated the potential use of our model for decision making purposes. With a given price and risk attitude, a decision maker could easily find the desired harvesting policy and at the same time see the consequences of deviations from this chosen policy.

For better understanding of the economic consequences of different management strategies it is necessary to develop the economic part of the model. In particular, studying the optimal management of the herring stock will be important in future research. In the context of risk analysis this would mean specifying decision criteria and risk attitudes for the management of Norwegian spring-spawning herring fishery.

Finally, other perspectives for developing the analysis would be, firstly, to implement the spatial and seasonal distribution of the fish and the fleets. Secondly, in the current paper, we have considered the management of Norwegian spring-spawning herring from the viewpoint of a single exploiter. However, there are several countries involved in the harvesting of the herring stock, which means that the management decisions should be carried out by international negotiations (see for example [9] and [10]).

References

- [1] Anonymous, editor. *Report of the Northern pelagic and blue whiting fisheries working group*, number Assess:14 in ICES Council Meeting Papers. ICES, Copenhagen, 1996.
- [2] Raymond J. H. Beverton and Sidney J. Holt. Section 6: Recruitment and egg-production. In *On the dynamics of exploited fish populations*, pages 44–67. Chapman & Hall, London, 1993.
- [3] Trond Bjørndal and Daniel V. Gordon. Cost functions for the Norwegian spring spawning fishery. Working paper 41, Foundation for Research in Economics and Business Administration (SNF), Bergen, Norway, 1998.
- [4] Trond Bjørndal, Astri Drange Hole, Wenche Margrethe Slinde, and Frank Asche. Norwegian spring spawning herring – some biological and economic issues. Working paper 29, Foundation for Research in Economics and Business Administration (SNF), Bergen, Norway, 1997.
- [5] Trond Bjørndal, Veijo Kaitala, Marko Lindroos, and Gordon Munro. The management of high seas fisheries. Working paper 1, Foundation for Research in Economics and Business Administration (SNF), Bergen, 1998.
- [6] Colin W. Clark. *Mathematical bioeconomics: the optimal management of renewable resources*. Pure and Applied Mathematics. Wiley-Interscience, New York, 1976.
- [7] R. I. C. C. Francis and R. Shotton. “risk” in fisheries management: a review. *Can. J. Fish. Aquat. Sci.*, 54:1699–1715, 1997.

- [8] Ray Hilborn and Carl J. Walters. *Quantitative fisheries stock assessment: choice, dynamics & uncertainty*. Chapman & Hall, New York, 1992.
- [9] Veijo Kaitala and Marko Lindroos. Sharing the benefits of cooperation in high seas fisheries: a characteristic function game approach. *Natural Resource Modeling*, 11(4):275–299, 1998.
- [10] Veijo T. Kaitala and Gordon R. Munro. The conservation and management of high seas fishery resources under the new law of the sea. *Natural Resource Modeling*, 10:87–108, 1997.
- [11] K. R. Patterson. Biological modelling of the Norwegian spring-spawning herring stock. Report 1, Fisheries Research Services, Aberdeen, January 1998.
- [12] Suzanne Touzeau, Veijo Kaitala, and Marko Lindroos. Implementation of the Norwegian spring-spawning herring stock dynamics and risk analysis. Systems Analysis Laboratory Research Reports A75, Helsinki University of Technology, September 1998.