OPTIMAL BIOECONOMIC MULTISPECIES FISHERIES MANAGEMENT:
A BALTIC SEA CASE STUDY

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ABSTRACT

We assess cod, herring, and sprat fisheries in the Baltic Sea under different salinity conditions using a bioeconomic model with simple predation functions. We compare the current fishing policy to an optimal policy under two different salinity conditions, which have a link to climate change. The fishery of these species is not at the most profitable level. If the fishing mortalities are lower, economic return will be greater in the long run. A lower fishing mortality for cod, which allows time for individuals to grow and achieve a higher economic value and reproduction potential, would result in the recovery of the cod stock. Under a high salinity level, which leads to better conditions for cod recruitment, the cod stock has a better chance to recover even without a decrease in fishing mortality. Therefore, fishery management is even more important under conditions of low salinity, which are likely to prevail in the future due to changing climate.

INTRODUCTION

Baltic cod *(Gadus morhua callarias),* Baltic herring (*Clupea harengus membras),* and sprat *(Sprattus sprattus)* are the most commercially exploited fish species in the Baltic Sea [1]. However, the valuable cod stocks have declined, and have thus affected negatively the economic profits. Since 1985, cod catches have rapidly decreased, and simultaneously sprat catches – a prey species of cod – have increased remarkably [1,2]. The reason for lower cod catches was – in addition to high fishing pressure – the low salinity and oxygen levels for cod recruitment. There is evidence that climate change will continue in this century [3], which may have decreasing effects on the salinity level in the Baltic Sea [4,5]. This is due to changes in the atmospheric circulation and therefore salt water pulses from the North Sea, which have become more seldom in the last decades [6,7]. In addition, salinity is affected by a general increase in precipitation with a simultaneous increase in the runoff of river flows, which have been estimated to increase even more due to climate change [8,9]. We incorporate a salinity factor into the model because it heavily affects cod recruitment success.

These three species have special interactions. Cod is the main predator fish in the Baltic Sea, and it feeds on herring and sprat. In addition, both cod and sprat eat cod eggs, and adult cod feed on young cod. The interactions have effects on the development of the fish stocks in the Baltic Sea and an important influence on both biological and economic performance.

We develop a deterministic, discrete, multispecies bioeconomic model for cod, herring, and sprat concerning the Baltic Sea fishery. The aim is to find the economically optimal fishing mortalities for these species. This is done by constructing a numerical model combining biological and economic factors. The optimization is conducted from the viewpoint of a fisheries management planner, and the aim is to maximize the social welfare of the entire fishing industry. After constructing the model, we compare four different scenarios.

BIOECONOMIC MODEL
Population dynamics
The number of individuals in each age class at each time period is the number of individuals survived from previous age class at previous time period. The spawning stock biomass is the sum of the biomass of mature fish over all age groups. The recruitment function for herring and sprat is modeled using Ricker's density dependent formation, as in ICES [1] and Heikinheimo [10]. Cod recruitment follows a function according to Hilborn and Walters [11] with a salinity factor that has been applied by Heikinheimo [10,12]. Each age class face annual harvesting following the formation of Hilborn and Walters [11]. We assume that only cod in age groups 3-8 are harvested and that the harvesting of herring and sprat involves age groups 2-8. Fishing mortalities are constant for each harvested age group.

The main interactions in the model are cod predation on herring, sprat, and young cod. We use predation mortality *M2* to illustrate the predation effect towards herring and sprat. We estimate *M2* using the predation function according to Heikinheimo [10] where the predation mortality is the number of cod individuals in each age class times the number of how many individuals of prey species one cod consumes divided by the total number of prey species.

Other interactions have also been taken into consideration. Based on the results of ICES [13], herring benefits from a lower sprat stock, which occurs when the cod abundance is high. This happens due to the increased abundance of food, and the mean individual weight in the herring spawning stock increases under these conditions. We modeled the mean weight in the herring spawning stock to be dependent on cod density as in Heikinheimo [10]. The interaction between cod and young cod, *i.e.* cannibalism, is not directly incorporated into the model, but it has been taken into consideration through the employment of a higher natural mortality rate for young age groups when cod is abundant.

Economic model
We used two different cost functions based on earlier literature. These functions have been observed to be illustrative for describing the harvesting costs of these differently behaving species. The cost function for cod follows a non-linear format as in Arnason *et al.* [14]. According to the function, an increase in cod biomass decreases harvesting costs because the fish are then easier to locate. For herring and sprat, the costs are linear function of fishing effort according to Gordon [15]. We assume that price is constant for each species. The prices are calculated based on a report of European Commission [2], representing the averages of several years of prices in the Baltic Sea coastal countries.

Bioeconomic optimization
The aim of the bioeconomic analysis is to solve the optimal fishing mortalities *F* over the time period. We construct a deterministic, discrete fishery model and use a simulation period of 50 years with a one-year time step. The starting values are the averages of the years 2006-2008 according to ICES [1], and the simulation period is 2009-2058. To solve the economically optimal fishing mortality paths, we first form an objective function and then maximize the net present value (NPV) over the simulation period under the biological constraints. We conduct the optimization by using MATLAB software.

RESULTS
We simulate the model under four different scenarios. The first scenario is the current situation with current fishing mortalities under low salinity conditions. Scenario 2 is also conducted under these conditions, but in this case we optimize the fishing mortalities. Scenarios 3 and 4 consider situations under higher salinity conditions with current and optimal fishing mortalities. All the main results of each scenario are presented in Table I. Next, we take a closer look of each of them

2

Table I: Average steady states of the scenarios

	N_c	N_h	N_s	SSB_c	SSB_h	SSB_s	F_c	F_h	F_s	H_c	H_h	H_s	NPV
Scenario 1	0.7	66	190	0.2	0.9	0.9	0.59	0.24	0.47	88	200	300	1.8
Scenario 2	1.5	75	240	0.5	1.6	1.3	0.28	0.21	0.05	160	310	57	5.3
Scenario 3	5.5	49	10	1.0	0.9	0.04	0.59	0.24	0.47	570	200	11	12.1
Scenario 4	5.5	51	48	1.4	1.0	0.2	0.42	0.03	0.01	570	40	0.8	15.4

N=stock size in numbers (thousands of millions), SSB=spawning stock size (millions of tonnes), F=fishing mortality rate, H=catch (thousands of tonnes), NPV=net present value (billion €); subscripts *c*, *h*, and *s* refer to cod, herring, and sprat, respectively.

Low salinity
The current fishing mortalities that we used were 0.59 for cod, 0.24 for herring, and 0.47 for sprat. These mortalities are averages from the years 2006-2008 and are based on ICES [1] for the entire Baltic Sea. With current fishing mortalities the population stock sizes in numbers of all species will decrease slightly in the simulation period as will the catches of herring and sprat. Instead, cod catches increase a bit due to a positive change in the age structure, which leads to a stock with older and heavier individuals. The net present value in the simulation period in Scenario 1 is €1,800 million.

When we optimize fishing mortalities to maximize economic profits in the simulation period, average cod mortality should decrease from 0.59 to 0.28, herring from 0.24 to 0.21, and sprat from 0.47 to 0.05. In this case the harvesting of cod and herring results in pulse or periodic fishing, in which harvesting does not necessarily occur every year.

In the optimum of Scenario 2, the cod stock recovers due to lower fishing mortality. Therefore, even if the fishing mortality is lower than before, catches are higher and so are profits: lower fishing mortality may yield higher catches in the long run. Sprat, which is the least valuable of these species, should be harvested much less in the optimum of this scenario. This is due to its low price and also to the high predation mortality by cod: higher cod stock effectively restricts sprat stock. The net present value in Scenario 2 is €5,300 million.

High salinity
The situation would be quite different if environmental conditions improved and more saline water flowed into the Baltic Sea. The cod stock would increase almost seven times compared to the current situation. This would have major effects on the prey stocks, which would decrease due to the increased predation mortality by cod. The fishery yields €12,000 million in profits in the simulation period. This is almost seven times higher than in Scenario 1 and over twice as high as in Scenario 2.

When we optimize fishing mortalities under high salinity, substantially more cod can be harvested due to the higher cod recruitment success, and optimal fishing mortality is 0.42. This mortality rate is still lower than currently. Even if the salinity level increases, the current fishing mortality level of cod would be too high and ought to be lower to achieve the economic optimum. With higher salinity, the abundance of cod is so high that less herring and sprat are available to harvest because of the high predation by cod. Therefore, fishing mortalities of herring and sprat are very low.

Cod stocks, in numbers, are about the same in Scenarios 3 and 4. The stocks are at their maximum, which they do not exceed due to very high cannibalism of young cod. Although cod catches are almost the same in Scenarios 3 and 4, the net present value is still even higher in Scenario 4. This is due to a decrease in the relatively costly herring and sprat fishery.

CONCLUSIONS

The fishery of cod, herring, and sprat in the Baltic Sea is at present profitable, but the profits could be higher if fishing mortalities were optimized. Under current salinity conditions, profits would be maximized if the fishing mortalities of all species were lower. Optimal mortalities yield total profits that are almost three times higher in the simulation period than in Scenario 1. The net present value increases due to the recovery of the cod stock, which both yields higher catches and lower harvesting costs in the long run. The fishery shifts to harvest more valuable species.

Under improved salinity conditions in Scenario 3, the net present value would be almost seven times higher than in Scenario 1 even with current fishing mortalities. Higher salinity level would increase the cod stock remarkably and furthermore affect herring and especially sprat stocks negatively, and their harvests almost disappear. When the fishing mortalities are optimized, the net present value would be even higher. Still, even under higher salinity conditions the optimal fishing mortality of cod would be lower than currently.

In Scenario 2, the net present value becomes almost three times higher compared to Scenario 1, but the proportional increase is much less in Scenario 4 compared to Scenario 3. According to this, fishing regulations are relatively more important when we have low salinity conditions. With better cod recruitment the amount of cod is high enough for the fishery to be very profitable even without strict regulations.

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