International Management Strategies for a Migratory Fish Stock: A Bio-Economic Simulation Model of the Norwegian Spring-Spawning Herring Fishery

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Abstract. In this paper, a three-country dynamic bio-economic model is presented and used to simulate catch levels, stock size and profit potential of alternative management strategies for the Norwegian spring-spawning herring fishery. Management of the herring fishery is complicated by the migratory behaviour of the species moving between coastal state zones and the high seas. The biological model is described by a discrete time age structured model and the economic model is described by a rent maximising model with constant price of herring and different costs of harvesting and efficiency levels for the different national fleets. The simulations are carried out over a 70-year period and show that the benefits of international co-operation far exceed the returns of a competitive open access fishery.

Keywords: Dynamic Bio-economic Simulation, Migratory Species, Management

1. INTRODUCTION

The Norwegian spring-spawning herring (*Clupea harengus*) stock is the most abundant fish species in the North Atlantic (Bjørndal *et al.*, 1998). Technological advancements in harvesting combined with open access management for both coastal states and the high seas fishery allowed for increases in catch levels and resulted in a collapse of the stock of spring-spawning herring by the end of the 1960's[1]. A fishing moratorium was imposed in 1970. However, it took 20 years for the stock to reach the Minimum Biological Acceptable Level (MBL) and only in the 1990's has the stock reached a point where Total Allowable Catch (TAC) levels increased.

The Norwegian spring-spawning herring fishery represents a serious challenge for international fisheries management if the consequences of open access are to be avoided. The task is made more complicated by the migratory behaviour of the species. If the stock of fish is abundant, an international migratory cycle is maintained that extends from Norwegian coastal waters, to international waters of the North Sea and finally, to Icelandic coastal waters. While the stock is in coastal waters the authority for fisheries management lies with the individual country. On the high seas the stock is open for harvesting by many fishing nations. If the stock is in a depleted state, as it was in the late 1960's, the species remains in Norwegian coastal waters and under Norwegian fisheries management jurisdiction. Consequently, Norway has a pivotal role in deciding fisheries management policies.

The purpose of this paper is to report the results of a dynamic bio-economic simulation model used to evaluate the consequences of alternative management strategies for the Norwegian spring-spawning herring fishery. The model characterises the harvest strategy for three national fleets that fish the Norwegian spring-spawning herring: Norway, Iceland and the European Union. The fleets are differentiated by cost and harvest efficiency. For each management alternative, the model simulates the consequences for both the biomass of the fish stock and the net profitability of the different fleets. The biological component of the model describes the population dynamics of the spring-spawning herring stock using a discrete time age structured model. The economic component describes the production technology and harvesting strategy for each of the three national fleets.

Five fisheries management strategies are evaluated. Open access is the base case showing the cycle of stock collapse and eventual recovery. The second case is defined by imposing a simple regulatory scheme of complete fishery closure on the open access case as the stock reaches critically low levels. Third, the stock is restricted to a depleted non-migratory state, remaining only in Norwegian waters and solely under Norwegian fishery jurisdiction. The fourth case investigates the consequences of monopoly control for Norway over an abundant migratory fish stock. In this case, side payments (rather than catch levels) are allocated to other states allowing Norway to maintain monopoly control. The last case allows for an abundant migratory fish stock under international fisher-

[1] See Gordon and Klein (1999) for a discussion of the Canadian North Atlantic cod fishery, where a fishing moratorium has been imposed since 1992.

ies management, where each participating state receives a share of the total catch.

2. SPRING-SPAWNING HERRING FISHERY

In the 1950`s and the 1960`s, Norwegian spring-spawning herring (*Clupea harengus*) was a major commercial species, harvested by vessels from Norway, Iceland, Faroe Islands, the former Soviet Union and several European nations. During this period, the fishable component of the herring stock is believed to have measured about 10 million metric tonnes (MT). However, during this period the stock was subjected to heavy exploitation by several European nations especially Norway, Iceland and the former Soviet Union, employing new and substantially more effective fishing technology. The annual harvest peaked at 2 million MT in 1966. By this time, however, the stock was in serious decline and a complete stock collapse occurred by the end of the decade. Finally, in 1970, a fishing moratorium was declared. Prior to stock depletion, the species was a straddling stock migrating through several coastal states and the high seas. Because of over fishing and poor recruitment, the spawning biomass fell precipitously in 1968 and 1969, leading to near extinction by 1972. In its depleted state, the adult population ceased migration and both adults and juveniles remained in Norwegian waters. The stock has re-established itself on the spawning grounds. For 1999, the TAC was 1,3 million MT and for 2000 the TAC is set at 1,25 million MT.

The recovery of the Norwegian spring-spawning stock offers the opportunity for annual harvests on a sustainable basis. It is clear that if the current co-operative arrangement among the countries fails and there is a return to the open access conditions of the early 1990s, this will result in increased international competition for harvest shares that will be biologically, economically and politically damaging. This could threaten a new stock collapse and result in substantial economic damage for all nations concerned in terms of lost revenue and employment.

3. A BIO-ECONOMIC SIMULATION MODEL

In modelling, we assume that the fundamental differences and characteristics of the international spring-spawning herring fishery can be captured in a three-agent model. The agents are defined based loosely on historical coalitions in the fishery. Norway and Russia have shown some co-operation in respect to resource management and setting of quotas, and we treat these two countries as one economic agent referring to the coalition as Norway. Similarly, Iceland and Faroe Islands have co-operated in setting catch level shares. As well, for these two countries the fishing grounds overlap and the harvest technology employed is similar. We will thus treat Iceland and Faroe Islands as one agent called Iceland. Several European countries, all of whom are members of the European Union (EU), also participate in the fishery using similar technology. Therefore, we will consider the EU as the third agent in the fishery.

In Norway, three different harvest technologies are employed (coastal vessel, trawler and purse seine) in the spring-spawning herring fishery (Bjørndal and Gordon, 1998). Cost of harvesting and quality of catch depends on the technology employed. However, in terms of quantity landed and harvest efficiency, purse seine is the most important vessel type. For this reason, the specification of the cost function for the Norwegian fleet used in simulation is based on the purse seine technology. As well, for consistency, the harvest cost functions for Iceland and the EU are also based on the purse seine technology. Regardless of the similar technology used in the fishery, the cost of harvesting may still vary across the national fleets. This is because even if the underlying technology is the same, certain aspects of the technology such as boat and engine size may still vary, and input prices for factors of production may be different. Moreover, individual boat quotas may vary from country to country. Even more importantly, the distance to the fishing grounds will be systematically different for the three economic agents. Based on this specification, Norway is assumed to be the most efficient harvester, followed by Iceland and then the EU.

The model describing fish population dynamics is based on Patterson (1998). In this paper, we describe only the elementary features of the biological model and concentrate on evaluating the management alternatives.[2] The harvest model given in Junttila , Lindroos and Kaitala (1999) is modified to match the three national fleet case examined here. The parameters that characterise the cost structure for harvesting varies for each of the three national fleets and is based on results reported in Bjørndal and Gordon (1998).

A summary list of notation used in the equations of the model is listed at the end of the paper. The fish population is distributed in 17 age classes, beginning from recruitment age class 0. A classical Beverton-Holt stock-recruitment relationship is used in linking the number of recruits, R to the spawning stock biomass, SSB (Beverton and Holt, 1957). A Ricker discrete time age-structured model is used to define the population dynamics for the herring stock (Ricker, 1954), where

[2] See, Touzeau, Lindroos and Kaitala, 1998 for a complete description of the stock dynamics, and Bjørndal and Gordon, 1998 for specification and estimation of the harvest cost function.

$$N_{0,y} = R_y$$
$$N_{a+1,y+1} = N_{a,y} e^{-m_a - \sum_{i=1}^{3} S_{a,y,i} f_{y,i}} \quad (1)$$

The initial estimate of $N_{a,o}$ is based on historical data and $N_{a,y}$ is the number of fish of each age class in each year with recruitment R_y.

All age classes are subject to natural mortality, m_a but mortality is substantially higher for juvenile (0.9) than for mature (0.15) fish. The age classes are also submitted to a rate of harvest, which is defined by means of a fishing mortality term $f_{y,i}$, and is related to the effort applied by the different national fleets to the stock each year. A selectivity rate, $S_{a,y,i}$ sets the vulnerability of each age class.

In this work, we use the simple density-independent model, which means using the annual constant averages from historical data in certain age class dependent variables.[3] The total population biomass in year *y* is expressed by

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

It is assumed that only the older component of the population (from age class 7 on) is fully mature, whereas the younger age classes (age class 0-3) do not spawn. The intermediate age classes are only partially mature. In the density-independent model we estimate the maturity ogive which defines the proportion of the mature individuals among the age class as constant averages, MO_a, for each age class. The annual spawning stock biomass is given by

$$SSB_y = \sum_{a=0}^{16} MO_a SW_a N_{a,y}. \quad (3)$$

The term SSB defines the spawning stock biomass as kilograms of the proportion of the annual number of fish.

The population dynamics model has been evaluated and calibrated in Junttila, Lindroos and Kaitala (1999). The biological simulations do well in predicting declines in the stock of fish over the different time periods studied but, as stated in Junttila , Lindroos and Kaitala (1999), the density-independent model is less satisfactory in predicting stock increases. The economic model is combined with the density independent population model to define catch and harvest relationships for the different national fleets.

The catch for fleet *i* in numbers is defined in terms of the fleet's share of total catch and natural mortality of the stock:

$$C_{a,y,i} = \frac{S_{a,y,i} f_{y,i}}{m_a + \sum_{i=1}^{3} S_{a,y,i} f_{y,i}} (N_{a,y} - N_{a+1,y+1}). \quad (4)$$

The catch weights at each age, which differ from the stock weights, are estimated as constant averages, CW_a, from historical data. Combining Equations (1) and (4) the annual total yield $TY_{y,i}$ for fleet i is obtained:

$$TY_{y,i} = \sum_{a=0}^{16} CW_a N_{a,y} * \frac{S_{a,y,i} f_{y,i}}{m_a + \sum_{i=1}^{3} S_{a,y,i} f_{y,i}} (1 - e^{-m_a - \sum_{i=1}^{3} S_{a,y,i} f_{y,i}}). \quad (5)$$

The rate of catch for each fleet *i* is controlled via two parameters, fishing mortality, $f_{y,i}$ and selectivity, $S_{a,y,i}$.

Fishing mortality is related to the effort applied by fishers on the stock and is considered a control term. The realistic range for the total fishing mortality based on historical data would be $\sum_{i=1}^{3} f_{y,i} \in [0,2]$. In simulation control, we assume that individual components can be modified to reflect the realistic capability for each fleet *i* in imposing fishing mortality. In simulation, fishing mortality is set at 1.0, 0.9 and 0.6 for Norway, Iceland and the EU, respectively. The different mortality rates reflect differences in cost/harvest efficiency of the different fleets.

Selectivity depends on the interaction between fish and vessel technology. The selection parameter is defined as, $S_{a,y,i} = 0, \ \forall a < a_{1,y,i}$ for age classes that are not harvested by fleet *i* and $S_{a,y,i} = 1, \ \forall a \geq a_{1,y,i}$ for age classes that are harvested by fleet *i*. For control purposes, we assume that the first fishing age is for age class 4.

The annual profit per fleet depends on the total annual yield $TY_{y,i}$ and the total annual costs $TC_{y,i}$. The economic or harvest component of the simulation model uses a constant cost function for levels of spring-spawning stock greater than 5 million tonnes and an exponentially rising cost for levels of spring-spawning stock less than 5 million tonnes. For each fleet *i* the total costs are

[3] See, Kitti, Lindroos and Kaitala, 1998 for an example of density-dependent growth of the population.

$$TC_{y,i} = \left({TY_{y,i}}\Big/{10^7} \right)^{\alpha_i} + \beta_i \,, \text{ if SSB} < 5*10^9 \text{ Kg}$$
$$TC_{y,i} = \beta_i \,, \qquad \text{if SSB} \geq 5*10^9 \text{ Kg.} \qquad (6)$$

Parameter values for α_i and β_i for Norway, Iceland and the EU are shown in Table 1.

Table 1. Cost Parameters and Price of Fish

Agent	α	β	h
Norway	-0.25	0.4	1.60 NOK/kg
Iceland	-0.3	0.7	1.35 NOK/kg
EU	-0.6	1.3	0.95 NOK/kg

The economic objective is to maximise profit or rent in each time period. As the planning horizon extends for many years, net profit comparisons for the three national fleets for alternative management strategies are based on the present discounted value of profit or

$$P_{y,i} = \frac{h_i * TY_{y,i} - TC_{y,i}}{(1+r)^{y-y1}} \,, \qquad (7)$$

where we assume a discount rate of r = 0.04.

Optimal harvest strategy contains optimal effort (optimal number of vessels) and optimal possibility to select the catch. Thus, based on the sensitivity of the annual catch and the size of the population on the rate of fishing mortality and selectivity, the fleets are able to adjust the effort to the current situation. The adjustment occurs with a lag effect and is constrained due to the investments on the vessel and gear. Even in an open access situation the share of the harvest is partly limited because of the reaction capability of the fleets. The national fleets are able to react rapidly when it comes to increasing effort, while reducing effort tends to be much slower (Bjørndal and Conrad, 1987). The simulation model is implemented as a Matlab routine and discussed in detail in Touzeau, Lindroos and Kaitala (1998).

4. MANAGEMENT STRATEGIES

Five strategies are evaluated for managing the spring-spawning herring fishery. We evaluate a broad range of managerial behaviour from the competitive open access to international co-operative arrangements in managing the fishery. One robust result of the simulation work is that the competitive open access fishery provides lower net returns and maintains lower stock levels compared to any of the co-operative solutions investigated. However, given that for this international fishery open access has historically been the prime management tool of choice, we define this as the base case in which to compare more co-operative outcomes.

In the open access case, no restriction is placed on the harvesting strategies of the agents defined in the simulation model. We assume the objective of each fleet is to engage in harvesting for the purpose of maximising profits. In a competitive open access fishery, each fleet will continue to extend its fishing effort as long as total cost is less than total revenue. Fishing effort extended by individual fleets is measured by a fishing mortality index and is a function of harvest efficiency. (A fishing mortality index of 1.0, 0.9 and 0.6 is maintained for Norway, Iceland and the EU, respectively.) In an open access profit maximising environment, the fleets will have incentive to continue harvesting until profit or rent has been dissipated (i.e., the classical tragedy of the commons). The simulations for harvest levels, fishing mortality, spawning stock biomass and net profitability are carried out over a seventy-year period. Figure 1a, shows spawning stock biomass and Figure 1b shows net present value of returns.

The simulations are based on an initial spawning stock biomass taken from mean data for catch, abundance and maturity for the actual stock of spring herring for the period 1993-1996. For the first few years harvest levels and fishing mortality increase and all three fleets show similar catch levels and rising profit levels. As harvesting continues the spawning stock biomass declines and this is reflected in decreased catch levels. Declining yields, however, do not diminish fishing effort because revenue continues to exceed total cost and fishing effort increases. For all fleets total fishing effort is achieved after the initial five years of harvesting. Each fleet maintains its maximum fishing effort over the next 12 to 15-year period regardless of the declining stock biomass and catch levels. What is more, fishing effort only starts to decline after the stock biomass falls far below the safe biological level (SSB) and approaches near collapse.

The reason for this excessive fishing effort in the face of serious stock decline is that in a competitive open access environment restraint on fishing effort by one fleet will only mean that another fleet will harvest the catch and, therefore, each fleet has incentive to continue fishing. This is the basic problem of the commons and is a result of the lack of well-defined property rights over the stock of fish.

Based on the economic and biological parameters of the spring-spawning herring fishery, the simulation model predicts that harvesting will continue with ever-declining catch levels until the stock collapses. After the collapse the population dynamics shows that about 20 years are required for the stock to enter a recovery phase. A complete stock recovery even to the average 1993-1996 levels is not possible because in the open access case a positive stock response immediately initiates harvesting and the cycle, albeit at a much lower amplitude, repeats. It is interesting that in the stock recovery phase only Norway and Iceland find it profitable to expend total fishing effort to harvest. The EU shows only moderate fishing effort and fishing mortality. Net profitability mirrors closely the fortunes of catch levels increasing only during the initial phase of harvesting and, thereafter, declining continuously until the stock is depleted and net profits fall to zero.

For the spring-spawning herring fishery open access competitive harvesting is inadequate to maintain a healthy biological stock and, clearly, the long-term economic benefits are minimal. However, it is interesting that within an open access regime the simple management strategy of complete fishery closure as the stock falls below the safe biological level (SSB) has substantial positive consequences for both stock and profit levels.

In Figures 2a-2b, we show simulation results for spawning stock biomass and net profitability, respectively, for open access harvesting with a management strategy of fishery closure. There are a number of interesting changes to the open access outcomes resulting from this simple management practise. The figures show four cycles of the simulation for this management regime. The initial cycle mirrors that of the open access until the stock decline reaches the safe biological level and closure is imposed. At this time catch levels and profits are set to zero. However, because closure is enforced prior to stock collapse and more fish are alive to spawn recovery occurs more rapidly compared to open access. Stock levels will fall somewhat below the safe biological level, which reflects the time required by the fleets to reduce fishing effort to zero. With stock recover in the second phase of the cycle harvesting resumes and profit taking occurs. The length of time with zero catch and zero profit levels is substantially reduced compared to the open access position. During the second phase, stock recovery is substantial and we observe increases in biomass two times greater than the average stock levels for the 1993-99 period. This is an important prediction from the simulation model and shows that a simple co-operative outcome of adhering to fishery closure allows for significant increases in stock size and catch levels over the simulation period. In the recovery period, the results show an increase in profits earned especially for Norway and Iceland compared to open access. Profits appear lower in the third and forth phase of the cycle compared to the previous cycle due to discounting.

Open access with fishery closure shows great improvement in stock and profit levels over the unfettered open access regime, but it does require a minimal of international co-operation in following the order for fishery closure. Norway as the pivotal and efficient harvester in the international fishery could exclude all other parties from fishing spring-spawning herring by maintaining the stock at below migratory levels and thus corralling the stock in Norwegian waters. It is estimated that the spawning stock biomass must be below 500 thousand tonnes to achieve non-migratory conditions. For Norway the important question is whether such a restrictive stock policy would provide sufficient benefits to make the effort worthwhile.

In Figures 3a-3b, the spawning stock biomass and net profit are shown for a 79-year simulation period for a non-migratory fish stock. The additional 9 years are required to deplete the stock to a non-migratory level and to allow a 70-year simulation period for comparison purposes with other management schemes. The economic objective characterising the harvesting process is not the simple open access behaviour of harvest as long as revenue exceeds cost, rather it is a combined objective of maximising profits and maintaining a non-migratory fish stock.

The harvesting strategy is to engage in full fishing effort (i.e., fishing mortality equal to one) increasing harvest yields and most importantly forcing the stock of fish to a non-migratory biological level. After this point, the objective is to harvest at a monopoly profit maximizing position subject to biological control on the level of the stock. The control allows fishing effort to reach maximum levels (i.e., fishing mortality set to one) as stocks increase and to then rapidly curtail fishing effort (i.e., fishing mortality set to 0.5) as stocks decline. By controlling fishing effort in an on/off manner, harvest and stock levels are maintained in a low amplitude cycle over time.

There are a number of advantages and disadvantages to Norway relative to open access from a non-migratory management scheme. On the one hand, catch levels never fall to zero and thus there is continuous uninterrupted employment, albeit at a low level, for the Norwegian fishery. At the same time, profit levels although reduced are maintained at above zero levels. On the other hand, profit levels are dismal and net present value declines overtime (because of discounting) monotonously towards zero. Although Norway has the benefit of sole management and control of the fishery, the non-migratory management scheme produces economic results that make Norway comparatively worse-off than the competitive open access position. If a Norwegian objective for the fishery is to maximise the economic benefits to Norwegians, a non-migratory management scheme falls far short relative to the open access with fishery closure or even the unrestrictive open access.

One obvious result of the three management schemes evaluated thus far is that international co-operation enhances the stock level and, perhaps more importantly, the economic benefits to all parties to the fishery. We explore further the possibilities for international co-operation by investigating the consequences of using side-payments to maintain a single fleet monopoly position over an abundant migratory fish stock, and of a co-operative cartel agreement to share a total catch quota for the fishery. The two co-operative schemes are similar in that the monopoly case allocates shares of the total rent, whereas, the cartel case allocates shares of the total catch. However, the economic difference in terms of potential profit is substantial.

The monopoly case is of special interest because it allows measurement of the total potential profits that could be generated in the fishery by harvesting the stock at the most efficient level. In simulations, Norway is defined as the low-cost efficient harvester. The harvest level for the monopolist is based on a constant fishing effort/mortality rate consistent with maximising monopoly profits. It is interesting, and in anticipation of the results, that we measure total net profits generated in the monopoly case as sufficient to more than compensate the non-participating fleets at a level greater than their best opportunity in the fishery and thus making such a management scheme economically viable.

Figures 4a-4b show spawning stock biomass, and net profits, respectively for the monopoly case. The simulations show that monopoly output is substantially different relative to the previous management cases examined. In contrast to open access, initially both the harvest level and spawning stock biomass decline rapidly. This is caused by the monopolist setting a fishing effort at a level consist with monopoly profit maximisation. The stock of fish eventually reaches a minimum point and increases due to strong year classes entering maturity stages. The stock is allowed to increase over time because fishing mortality does not respond to the stock of fish but only to profit maximisation. As this occurs, the harvest increases steadily and eventually reaches an equilibrium position. Nominal profits respond to harvest levels, showing an initial decline and then increasing to a stable level. Overtime, the spawning stock biomass reaches equilibrium within the monopoly profit maximising environment at about 6.5 million tonnes. This is not large compared to stock levels achieved in, say, open access with fishery closure, rather, it is the stability of the equilibrium overtime that distinguishes the stock effect of the monopolist from other cases investigated.

To capture the profit potential of the monopoly position requires a total commitment to international co-operation in the fishery, in terms of agreeing to share the total rent rather than share the total catch. An alternative strategy is to allocate a share of the monopoly harvest to each of the individual fleets. This allows all fleets to participate in the fishery but because the different fleets are characterized by different levels of harvest/cost efficiency, there will be a general loss in total profits earned in the fishery. The loss in potential profit between monopolist and cartel control of the fishery can be measured from the simulations.

Based on historical harvest levels Norway will receive the largest share (51%), then Iceland (29%) and the EU (20%). Once shares are allocated, each fleet will operate in an efficient profit maximising manner. In other words, each fleet will set a fishing effort/mortality rate to maximise profits over individual shares. This behaviour is analogous to that of the monopolist in terms of total harvest and spawning stock biomass for the fishery. Of course, the harvest and profit levels are shared among the three fleets.

In Figure 5, profit levels are reported for Norway, Iceland and the EU over the simulation period. With fishing effort/mortality rate set by profit maximisation, harvest levels first decline and then rise to an equilibrium level overtime for the same reason as under monopoly behaviour. Similarly, net profits for the three fleets show that Norway earns a substantial rent based on its cost efficient harvesting levels compared to Iceland and the EU. The differences in profit level at each point in time reflect the different efficiency levels across the different fleets.

The simulation results show that the monopolist earns greater profits in all periods compared to that of the cartel. An interesting question is whether sufficient additional profit is earned under the monopoly position to compensate other players to allow Norway to maintain the monopoly position?

Table 2. Total Discounted Profits

Net Present Value of Profit, 4% discount rate

Management Regime	**Norway**	**Iceland**	**EU**
Open Access	5.96[a]	4.24	1.52
Open Access with Fishery Closure	10.56	7.93	1.82
Non-Migration	4.79	-	-
Cartel	26.63	7.12	0.48
Monopoly	38.04	-	-

[a] all values are 10 to power 9

We address this question in Table 2 where net profit levels across the five alternative management strategies are listed. Keep in mind that nominal profit is discounted at 4% annually over a 70-year time horizon. First, comparing open access management to open access with fishery closure, all three countries are made better off in terms of higher net profits by engaging in minimal co-operation and by adhering to fishery closures. However, it is also clear that the benefits of co-operation are not equally shared across the different fleets. Norway sees an increase of 149%, Iceland an increase of 106% but the EU measures only a marginal increase of 43%. Both Norway and Iceland clearly benefit from co-operation in the fishery, whereas co-operation for the EU shows rather marginal benefits. Nonetheless, there is ample profits earned in the fishery between Norway and Iceland to offer side payments to make it profitable for the EU to adhere to fishery closure.[4] The alternative would be a return to open access where both Norway and Iceland would be worse off.

Second, we measure the overall net profitability of sole Norwegian jurisdiction over a non-migratory fish stock. In this case, Norway benefits in terms of maintaining total fisheries control over the spring herring stock, however, net profitability falls 13% of what could be obtained under simple open access and a substantial 65% decline in profit compared to open access with fishery closure. Clearly, a non-migratory herring fisheries policy is not credible and by allowing a migratory fish stock Norway benefits in terms of substantially higher profits for its industry.

The last scenario is to compare net profitability of the monopoly position with that of the cartel. In the cartel case, the simulation results are based on allocating harvest shares on historical catch levels for the three fleets. Table 2 shows that Norway would benefit substantially from this historical allocation showing an increase of 41% in net profits compared to open access with fishery closure. On the other hand, both Iceland and the EU see their net profits increase by 3% and 2%, respectively compared to open access with fishery closure. Because total profits under cartel arrangements are 25% higher than under open access with fishery closure, a different allocation of catch shares could be negotiated that would allow both Iceland and the EU to receive a larger share of total profit. The important question, however, is whether under monopoly harvesting in the international fishery could Iceland and the EU be sufficiently compensated to support such a position? That is, Iceland and the EU would become non-participants in the fishery but receive a share of the total rent. Our simulations show that allowing for efficient cost of harvesting net profits are 28% higher under a monopoly compared to cartel. In other words, by international agreement to share the total rent from the fishery rather than total catch all members to the fishery can be made better off.

[4] See, Kaitala and Lindroos, 1998 who show how using Nucleolus and Shapley values as solution concepts, surplus benefits of co-operation are shared in such a way that the two most efficient agents should receive a larger share relative to a third agent.

5. CONCLUSION

The purpose of this paper is to simulate the consequences for stock levels and net profit potential of alternative management strategies for the international spring-spawning herring fishery. Five alternative management schemes are evaluated. Open access is the base case showing the cycle of stock collapse and recovery. The second case is defined by imposing a simple regulatory scheme of complete fishery closure on the open access case as the stock reaches critically low levels. Third, the stock is restricted to a depleted non-migratory state, remaining only in Norwegian waters and solely under Norwegian fishery jurisdiction. The fourth case investigates the consequences of sharing among the three agents the rents obtained from monopoly harvesting over an abundant migratory fish stock. The final case allows sharing the total catch among the three agents for an abundant migratory fish stock under international fisheries management.

The simulation model does well in forecasting the outcome of competitive open access showing increased and sustained fishing effort by all fleets while harvest levels decline. Eventually, undiminished harvest results in stock collapse and demise of the fishery. A management restriction of fishery closure on the open access as stock falls below safe biological levels has substantial positive benefits for both the stock level and potential net profits to all participates in the fishery.

Examining the possibilities for Norway to maintain sole fisheries jurisdiction over a small non-migrating stock of herring corralled in Norwegian waters shows minimal benefits in terms of net profits to the Norwegian fishery. Compared to the competitive open access fishery, a non-migratory herring fishery policy leaves Norway much worse off and even more so compared open access with fishery closure.

Finally, we show that either a monopoly or a cartel position with an abundant migratory fish stock can bring significant benefits to all participates in the industry. Under monopoly the largest potential profits are earned in the fishery but international agreement is required to share the rent among the non-participates that would allow the monopoly to exist. Under cartel potential profits, although smaller than monopoly, are larger than under open access with fishery closure, but requires international agreement to share the monopoly harvest level. Whether international agreement allocates shares of rent or catch levels, management co-operation in the spring-spawning herring fishery can achieve substantial economic benefits for all participates to the fishery under sustainable stock levels.

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A Summary of Notation

Sub-scripts	Definition	Range	
a	**Age**	**{0,1,2,…,16} years**	
y	**Time**	**Current year**	
i	**Fleet index**	**Fleet**	
Variables	Definition	Unit	Subscripts
N	**Abundance**	**Numbers**	***a, y***
B	**Biomass**	**kg.**	***a, y***
SSB	**Spawning stock biomass**	**kg**	***y***
R	**Recruitment**	**Numbers**	***y***
C	**Total harvest**	**Numbers**	
TC	**Total Cost**	**NOK**	***y,i***
TY	**Total yield**	**kg**	***a, y, i***
CW	**Individual weight at age in the catch**	**kg/ numbers**	***a***
SW	**Individual weight at age in the stock**	**kg/ numbers**	***a***
MO	**Maturity ogive**	**%**	***a***
f	**Fishing mortality**	**-**	***y, I***
S	**Selectivity**	**-**	***a, y, i***
Parameters	Definition	unit	Subscripts
h	**Fish price per kg.**	**cf. table 1**	***i***
α, β	**cost function parameters**	**cf. table 1**	***i***

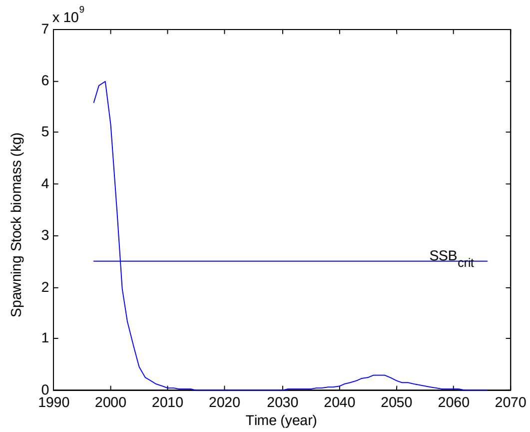


Figure 1a. Spawning Stock, Open Access

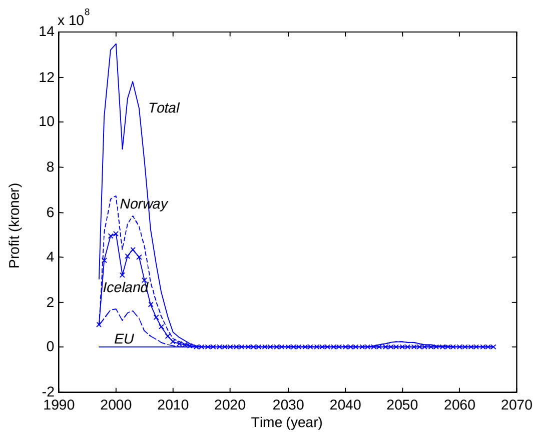


Figure 1b. Profit, Open Access

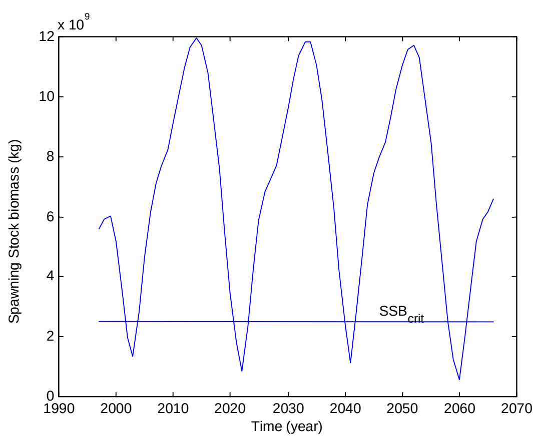


Figure 2a. Spawning Stock, Fishery Closure

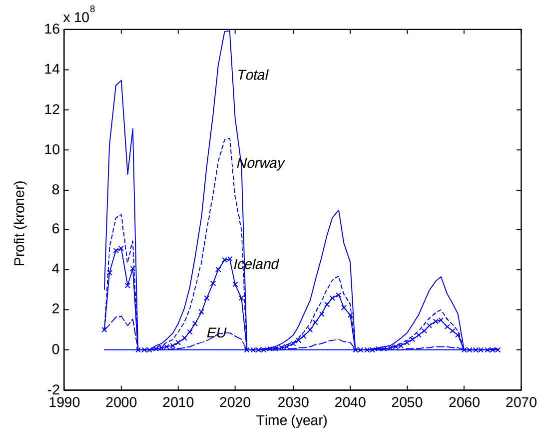


Figure 2b. Profit, Fishery Closure

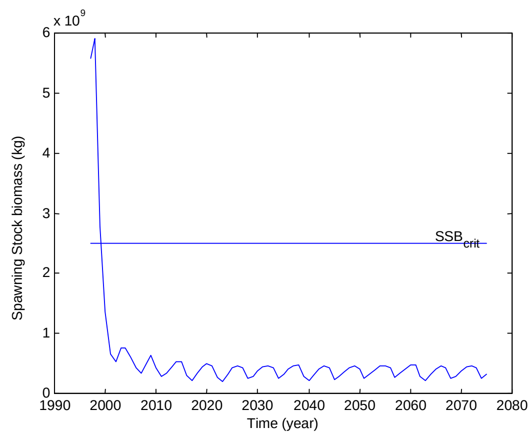


Figure 3a. Spawning Stock, Non-migration

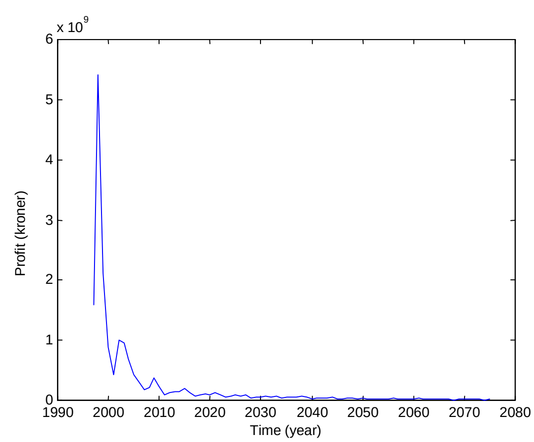


Figure 3b. Profit, Non-migration

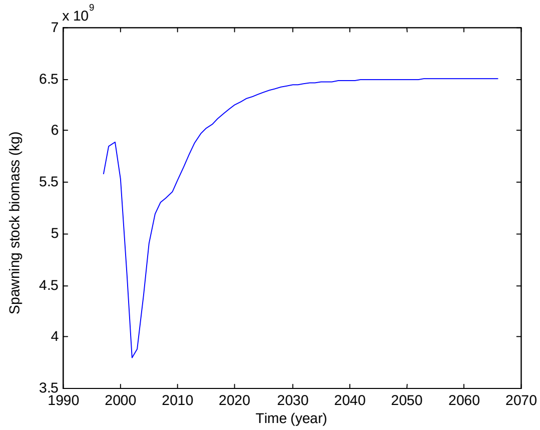


Figure 4a. Monopoly, Spawning Stock

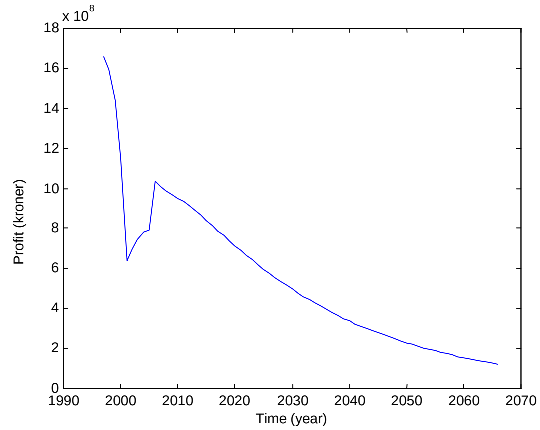
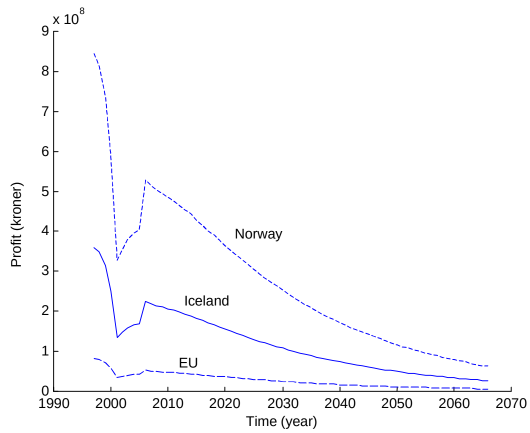


Figure 4b. Monopoly, Profit



Figures 5. Cartel Profit