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Sharing the Herring: Fish Migrations, Strategic Advantage, and Climate Change

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ABSTRACT

After the exclusive economic zone was established in the late 1970s, the European Union and Norway divided the catch quotas from the stocks in the North Sea according to the zonal attachment of the stocks. For most of the stocks affected these agreements have held up well, but for North Sea herring the agreement was disputed, because as the herring stock grew bigger it began to migrate more extensively.

The Norwegian spring spawning herring is also a stock whose migrations appear related to the size of the stock. After the stock crashed around 1970 it changed its migratory pattern and became confined to the Norwegian exclusive economic zone. As the stock recovered, it started to migrate into international waters and the economic zone of other countries. It would thus appear that Norway could keep the stock for itself if she fishes down the stock to a level low enough to prevent it from migrating out of the Norwegian zone.

This paper analyzes the strategic options of Norway and other countries for which the stock may be accessible. It is found that Norway would not necessarily be interested in totally preventing the migrations of the herring, even if other interested parties do not cooperate on managing the stock. When the other parties do not cooperate they would not leave behind anything of the stock that migrates out of the Norwegian zone, but would still be able to free ride on the conservation efforts of Norway as a dominant player. The other players in fact come out best if they only have access to a small part of the stock, because the incentive for Norway to conserve the stock will then be stronger than otherwise.

A cooperative solution would make all parties better off. In a cooperative solution Norway must obtain a relatively large share of the total catch quota, because of her strategic advantage. The critical share to be offered to Norway does not have anything to do with the zonal attachment of the stock, interpreted as the share of the stock within the Norwegian economic zone.

There are indications that the changes in the migration of the herring in the late 1960s were related to lower temperatures in the ocean north and east of Iceland where the stock foraged and wintered in the 1950s and 60s. A rise in the temperature in this area could mean a larger carrying capacity for the stock and more extensive migration. This in turn would mean a less strong attachment of the stock to the Norwegian economic zone, strengthening the bargaining position of other parties than Norway. It is shown that more extensive herring migrations could undermine an agreed division of the total quota for herring by making a non-cooperative solution more attractive for other parties than Norway. This would make a renegotiation of the agreement necessary, but this might not take place until after the other parties have broken out of the agreement and fished the stock competitively for some time, which would imply a major reduction in the stock and the sustainable yield.

INTRODUCTION

In the 1970s most coastal states established a 200-mile exclusive economic zone in their offshore waters, after the concept had been sanctioned by the then ongoing Law of the Sea Conference. In cases where the continental shelf does not extend further than 200 miles from shore, the fish stocks confined to the waters of the continental shelf (e.g., cod, plaice) became enclosed by the exclusive economic zone. Such stocks do, however, often migrate extensively, so that in cases where two or more countries share the same continental shelf, these stocks became the shared property of the countries between whose zones they migrate. Stocks that inhabit surface waters (e.g., mackerel, herring, tuna) usually migrate much more widely than bottom-dwelling fish and often transgress into the high seas outside the 200 mile zone of any country. In cases where the continental shelf protrudes out of the exclusive economic zone (e.g., the Grand Banks, the Barents Sea, the Bering Sea), even bottom dwelling fish straddle out of the exclusive economic zone.

A successful management of transboundary stocks requires that the countries having an interest in them agree on how they are to be shared and managed. In the late 1970s Norway and the European Union agreed to share the stocks that migrate between their zones according to the “zonal attachment” of each stock.¹ Zonal attachment can be defined and measured in various ways, and precisely how this is done can be controversial. Some fish may be spawned in the economic zone of Country A while not becoming fishable until they have moved into the zone of Country B, so whose fish is it really? Other types of fish may feed and be fattened in the zone of Country C but fishable mainly in the zone of Country D. In the agreements between the European Union and Norway zonal attachment was based on the presence of the fishable part of the stocks in each party’s zone in the years 1974-78 (Engesæter [1993], p. 94). In other contexts different approaches have been applied. One such uses biomass multiplied by the time migrating stocks spend in each country’s zone (Hamre [1993]). This was applied in the sharing of the capelin stock that migrates between the zones of Greenland, Iceland, and Jan Mayen, an island under Norwegian sovereignty (Engesæter [1993]). Instead of biomass this approach could be based on the growth of the stock (Hamre [1993]).

For most stocks in the North Sea² the agreement between Norway and the EU seems to have held up well, even if the zonal attachment principle is not necessarily compatible with the incentives of the individual countries (Hannesson, 2004). There have been problems, however, over North Sea herring. This stock fluctuates considerably in size because of environmental factors, and it changes its migratory behavior as it becomes more abundant. When the stock recovered in the 1980s from the breakdown in the 1970s it started to migrate further north and to a greater extent into the Norwegian exclusive economic zone. This made Norway unhappy with the 4 percent share she was being offered on the basis of the previous zonal attachment of the stock. For some time no agreement was in force between Norway and the European Union, and Norway fished the stock at will within its own zone after the herring moratorium was lifted in 1984. In 1986 a new agreement was concluded giving Norway a share of 25, 29 or 32 percent, depending on the size of the spawning stock (Engesæter [1993], p. 96).

As the North Sea herring example indicates, it is difficult to agree on sharing fish stocks whose migratory behavior and accessibility within individual countries’ economic zones changes with their size. If a stock is confined to a particular country’s economic zone when it

¹ On the concept of zonal attachment, see see ICES (1978) and Engesæter (1993).

² These stocks are cod, haddock, saithe, plaice, whiting, sprat and herring (Engesæter [1993]).

is sufficiently small, that country could easily have incentives to keep the stock down in order to prevent it from becoming accessible for others, at any rate if the other interested parties turn out to be recalcitrant in agreeing to a cooperative management plan. In any case it seems likely that the “core host” country would have a clear advantage when it comes to sharing the stock, as its threat point would be determined by what it would obtain if it had the stock all for itself.

The Norwegian spring spawning herring appears to be a stock of this kind. This stock spawns off the coast of Norway. The juveniles feed in the Norwegian economic zone, and the Russian zone if the stock is large enough. The mature stock migrates into the so-called Ocean Loop, an area not covered by the exclusive economic zone of any country, and into the Faeroese and the Icelandic zones (see Figure 1). These migrations appear to be related to how large the stock is. In this paper we analyze the strategic advantage Norway might have from being in a position to reserve the stock for itself by keeping it below the level where it starts to migrate out of the Norwegian zone. This does not necessarily mean that Norway would have an advantage in not sharing the stock with others, but it is likely to have a bearing on how the catches from the stock should be shared and what interpretations should be given to the zonal attachment principle, or whether that principle is of any interest for how the stock should be shared. Lastly we consider how an improvement in ocean climate, such as might result from global warming, could affect the Norwegian strategic position and the sharing of the stock. An increase in ocean temperature east and north of Iceland would most likely increase the migrations of the stock by increasing the supply of plankton in this area where the herring stock is now rarely found but where it was abundant in the middle of the last century.

THE NORWEGIAN SPRING SPAWNING HERRING

The story of the Norwegian spring spawning herring over the last fifty years or so is dramatic. In 1950 this stock may have been almost 20 million tonnes. Figure 2 shows the estimated abundance and the catches from this stock. In the 1950s and 60s the catches exceeded one million tonnes in most years. This was probably a lot more than the stock could endure, and in the late 1960s it crashed, reaching a minimum of less than half a million tonnes in 1972.

The migrations of the Norwegian spring spawning herring are complex but undoubtedly influenced by conditions in the ocean and, apparently, the size of the stock as well. Until the early 1960s the stock fed off the north coast of Iceland in summer (May to September), wintered east of Iceland (November and December), and migrated to the west coast of Norway to spawn in February and March.³ The young, immature year classes foraged in Norwegian coastal waters and in the Barents Sea. The summer feeding takes place in relatively warm, “Atlantic” water, which in summer is rich with plankton (*calanus finnmarchicus*). The cooling of the East Iceland current in the mid-1960s pushed the limit between Arctic and Atlantic waters further east (Malmberg, 1969; Malmberg and Jónsson, 2002), and the feeding migrations in spring and summer were diverted north towards Spitzbergen. After the crash around 1970 the stock ceased to migrate out of the Norwegian economic zone, wintering in Lofoten, but for the most part spawning further south off the

³ According to *Report of the Scientific Working Group on Zonal Attachment of Norwegian Spring Spawning Herring*, November 1995. The report was produced by a group of marine biologists from Norway, Iceland, the Faeroe Islands and Russia. It has not been formally published but is obtainable in draft form from the marine research institutes involved in the said countries. See also Vilhjálmsson (1997).

coast of Møre (see Figure 1). It is tempting to explain the less extensive migrations of the herring stock after 1970 by a lesser need for food by a small stock.

After the collapse further catches from the stock were banned, except that Norway permitted a small catch (7 - 20 thousand tonnes per year). In 1985 the stock showed signs of recovery, and boats from Russia began to catch fish from this stock. As the stock recovered further, after a short hiatus, the catches from other nations than Norway increased. From 1994 onwards boats from Iceland and the Faeroe Islands caught fish from this stock, and a year later boats from member countries of the European Union began to do so as well.

The fishing activity of nations other than Norway was due to the fact that as the stock grew bigger it began to migrate out of the Norwegian economic zone. This “spillover” first occurred into the Soviet zone in the Barents Sea, but as the stock increased further it started to migrate into the high seas and into the Faeroese and the Icelandic zones. The Faeroese and the Icelandic fisheries occurred partly in the zones of these two countries but also outside the exclusive economic zones, in the so-called “Ocean Loop” (see Figure 1). The fishing by the EU countries took place in the latter area, since this particular stock hardly ever migrates into the EU-zone. Figure 3 shows the spring migrations of the herring stock in recent years.

Increasing fishing by nations other than Norway led to efforts to control the fishery through international agreements. In 1999 an agreement was reached among all interested parties on the total quota to be allowed and its distribution. In 2003 this agreement fell apart, however, due to disputes among the countries involved about the division of the total catch quota.

Since the stock migrates further and wider the larger it is, the Norwegian share of the total catch depends on the size of the stock. The Norwegian share of the total catch taken from the stock is shown in Figure 4 together with the stock size. The share fell to about 85 percent in the late 1980s as the stock came to exceed 2 million tonnes. After that it stayed relatively constant despite a continued stock growth until it fell rather precipitously to about 60 percent in 1995. Since that time the stock has stayed relatively constant at about 8 million tonnes, and so has the Norwegian share of the catch. It would seem, therefore, that Norway has a dominant strategic position in the game about the herring. She could elect to fish down the stock to a level which would prevent it from migrating outside the Norwegian exclusive economic zone. While this is not necessarily the best strategy for Norway to follow it is likely to be important for how the spoils of the cooperative play would be divided.

PREVIOUS LITERATURE ON THE HERRING GAME

Two recent papers discuss the exploitation of the Norwegian spring spawning herring from a game theoretic perspective (Arnason, Magnusson and Agnarsson [2000], and Lindroos and Kaitala [2000]). Both papers focus on the forming of coalitions among the exploiting nations and on the scope for attaining a globally cooperative solution. These papers take different approaches. Lindroos and Kaitala identify three players, Norway/Russia, in whose zones the stock spawns and grows up; Iceland/Faeroe Islands, into whose zones the stock migrates; and the EU countries, which can fish the stock in the international area outside 200 miles. They use a year class model and assume that the unit fishing costs are inversely related to the exploited stock, an assumption that is probably unrealistic for the herring stock. They find that a fully cooperative solution is unlikely except if the fishery is rather inefficient (low catchability coefficient). Arnason, Magnusson and Agnarsson use a general biomass model

and consider explicitly the migrations of the stock between the economic zones of different countries, as well as its migration into the international area outside 200 miles. They assume that the cost of catching herring is unrelated to the size of the stock but related to the distance of the fishing locations from the home port of the boats. They identify five players, Norway, Russia, Iceland, the Faeroe Islands, and the EU. They find that a globally cooperative solution would require side payments to Norway and that many of the potential coalitions in the game would not be viable.

Neither one of these papers considers the possibility that the stock would be confined to the Norwegian economic zone provided it is small enough, making it possible for Norway to act as a sole owner and, in its own interest, conserve the stock just below this critical level. This would seem sufficient to prevent the nearly total depletion of the stock that occurs in some scenarios in Lindroos and Kaitala's model. The model of Arnason, Magnusson and Agnarsson gives an advantage to Norway, due to letting the stock originate in the Norwegian zone. This results in the need for side payments to Norway in order to make her interested in a cooperative solution. These side payments could take the form of Norway being allowed to fish in the economic zone of other countries (in the spatial model used by these authors no country is permitted to fish in the economic zone of another country unless explicitly permitted to do so). In the context of this present paper, this would amount to giving Norway a larger share of the herring stock than its zonal attachment would dictate.

This paper applies a general biomass model of the same type as Arnason, Magnusson and Agnarsson and focuses on the consequences of the migratory behavior of the herring stock being dependent on its size. While the model in this paper is applied to one particular stock it would seem that the whole approach is suggestive of what might happen in other cases where one particular country has an advantage similar to what Norway seems to have in this case.

THE MODEL

The herring fishery is modeled in discrete time, where fishing occurs at the beginning of each period, with growth taking place after the fishery is over and depending on the size of the stock left after fishing. Formally

$$X_{t+1} = G(S_t) + S_t$$

$$S_t = X_t - Y_t$$

where X is the stock at the beginning of a period, Y is the catch of fish during the period, and $G(\cdot)$ is the surplus growth of the stock (natural growth less decay). This general biomass model is used for simplicity; in reality the herring stock consists of several year classes of fish, and the surplus growth of the stock consists of the growth of all the different year classes in the stock in any given time period. In an appendix a year class model meant to reflect long term (average) conditions is discussed and contrasted with the general biomass model.

The most popular general biomass growth equation is the logistic:

$$G = rS(1 - S/K)$$

Used in the above equation we get the equation to be estimated:

$$X_{t+1} - S_t = \alpha S_t - \beta S_t^2$$

where the parameters of the logistic equation are $r = \alpha$ and $K = \alpha / \beta$.

A variant of the logistic equation is the asymmetric logistic

$$G = rS \left[1 - (S / K)^\gamma \right]$$

The Ricker equation, even if developed for a recruitment relationship, may also be used as a general biomass growth function:

$$X_{t+1} = S_t \exp(a(1 - S_t / K))$$

which can be estimated on logarithmic form as

$$\ln(X_{t+1}) - \ln(S_t) = \alpha - \beta S_t$$

where the parameters are $a = \alpha$ and $K = \alpha / \beta$.

Data on the stock size (X) and the catches (Y) of the Norwegian spring spawning herring since 1950 are published in ICES (2003), Table 3.3.3. From this we can calculate the stock left behind after fishing (S) as

$$S_t = X_t - Y_t.$$

Table 1

Estimation of a surplus growth function for Norwegian spring spawning herring.

	Logistic				Ricker			
	α	β	K	R^2	α	β	K	R^2
1950-2002	0.14407 (2.64)	-0.00725 (-1.74)	19.9	0.012	0.13912 (2.61)	-0.00793 (-1.09)	17.5	0.020
1950-1972	0.06020 (0.76)	-0.00181 (-0.33)	33.2	0.037	-0.03806 (-0.84)	0.00577 (1.28)	6.59	0.075
1972-2002	0.36310 (1.71)	-0.03653 (-1.14)	9.94	0.040	0.23553 (2.61)	-0.02158 (-1.09)	10.9	0.040

Table 1 shows the results of estimating the logistic equation and the Ricker equation (t-values are in parentheses), as well as the implied values of K . Results are shown for the entire period and for two sub-periods. The dividing line between the two sub-periods is the early 1970s when the stock had collapsed and radically changed its migratory behavior. It can therefore be argued that the growth parameters of the stock most likely changed as well after the early 1970s. We may note that the carrying capacity implied by both equations is rather similar for the entire period and for the period 1972-2002. The carrying capacity for the latter period is

close to 10 million tonnes, which is similar to what Arnason, Magnusson and Agnarsson (2000) found by a similar approach. The results for the entire period after 1950 indicate about twice as large carrying capacity, which could be due to the much wider migration of the stock in the 1950s and 60s. This is supported by the logistic equation for the period 1950-72, which shows a much larger carrying capacity for that period, about 30 million tonnes. The results obtained for the Ricker equation for that sub-period are, however, nonsensical, implying a negative value of the parameter a . In the 1950s the stock was between ten and twenty million tonnes (Figure 2).

It is evident from the low values of the R^2 s in Table 1 that neither of the two equations can explain much of the annual growth in the stock. The growth of the herring stock is much affected by variability of recruitment (i.e., size of new cohorts of fish being added to the stock). This variability is due to environmental factors which are poorly understood and which no model of stock-dependent growth can be expected to explain. That notwithstanding, a stock-growth model could make some sense for describing what happens under average conditions. Figure 5 shows the calculated annual growth ($G_t = X_{t+1} - S_t$) of the stock and the functions estimated for the period 1972-2002.

Figure 5 also shows an asymmetric logistic growth curve estimated by an optimization routine minimizing the sum of squared deviations between the calculated values of G and the values implied by the growth function. The skewness parameter is quite large (6.0), implying a surplus growth function that is heavily skewed to the right and a substantially higher maximum growth than the other two curves, but a lower carrying capacity. The year class approach discussed in an appendix indicates, however, that the surplus growth curve could be skewed to the left and not to the right. In the following we will use the symmetric logistic function with rounded-off parameters of $r = 0.36$ and $K = 10$, as the Ricker function seems to give a too low maximum sustainable yield and the asymmetric logistic a too great maximum sustainable yield and a curve that is skewed in the wrong direction.

The Norwegian share of the stock, or zonal attachment, (u) is assumed to be determined as follows:

$$u = \begin{cases} 1 & \text{if } S \leq \bar{S} \\ 1 - \frac{v(S - \bar{S})}{(K - \bar{S})} & \text{otherwise} \end{cases}$$

where \bar{S} is the critical stock level left after fishing at which the stock does not migrate out of the Norwegian zone and v is the maximum share others could obtain of the stock. Hence the Norwegian share of the catch falls uniformly from 1 as the stock increases from the critical level \bar{S} to the carrying capacity level K , where $u = 1 - v$. This is a simplification of the stepwise relationship produced by the catches in recent years and shown in Figure 4.

The herring is a schooling fish, for which it may be expected that the unit cost of fish does not depend on the stock.⁴ Under those circumstances the optimal exploitation of the stock is independent of prices and costs, except that the price must be high enough to cover the unit cost. If the price depends on the catch volume, this must hold at the margin. If the objective is

⁴ In a study of the North Sea herring, Bjørndal (1987) reported results that imply a very weak dependence of unit costs on the size of the stock.

maximization of the present value of the fishery over an infinite time horizon, the general condition for optimality is that the marginal rate of surplus growth of the stock should be equal to the rate of interest. Here we will for simplicity ignore time discounting and instead assume that the goal is to maximize the annual rent from the fishery.

THE COMPETITIVE SOLUTION

Let us look, first, at a competitive solution where there is no cooperation between the parties and each takes the stock level the other parties leave behind after fishing in their own economic zone as given. We simplify the setting to two players, Norway and the others. A justification for this is that in the competitive setting it turns out that the competitive players have incentives never to leave behind anything of the stock that migrates into their zone. This occurs because the stock they leave behind does not stay in their zone but migrates back into the Norwegian zone where it winters. This apparently accords with the present behavior of the stock. At the beginning of the next period (next spring) the stock migrates and spills over into other countries' zones and into the international area outside 200 miles according to the share parameters u and v explained above.

Maximizing the rent per year in a steady-state equilibrium entails, for Norway (N) and the others (O), respectively, maximizing each party's share of the sustainable yield:

$$u(S)[G(S)+S]-S_N$$

$$(1-u(S))[G(S)+S]-S_O$$

where $S = S_N + S_O$. The first order conditions are

$$u(S)[G'(S)+1]+u'(S)[G(S)+S]-1=0$$

$$(1-u(S))[G'(S)+1]-u'(S)[G(S)+S]-1=0$$

Obviously these cannot be satisfied simultaneously except if the stock is shared evenly among the two parties ($u = 0.5$). We conclude that while Norway will leave behind some of the stock in her zone, the others will take everything that straddles into their zone or into the high seas. They will still be able to benefit from what Norway leaves behind, because some of the stock that emerges at the beginning of each period will migrate out of the Norwegian zone, provided that the stock Norway leaves behind after fishing is large enough. In the non-cooperative setting, the others do not get a high enough return from any fish they might choose to leave behind.

Figure 6 shows how the optimal stock for Norway to leave behind changes as the maximum share of the others (v) increases. For a high enough maximum share for the others ($v > 0.6$), Norway keeps the stock down at the level below which it does not spill over into the others' zones or into the high seas ($\bar{S} = 2$). As v falls below 0.6, Norway leaves more fish behind, and some of the stock migrates out of the Norwegian zone. If the stock would always stay in the Norwegian zone no matter how large it is Norway would operate as a sole owner and leave behind half of the virgin stock.

Before examining the cooperative solution, let us look briefly at how the non-cooperative solution changes as a result of varying other parameters. Figure 7 shows how the optimal stock to be left behind by Norway varies with the level at which the stock starts to migrate out of the Norwegian zone. If this critical level is 3 or more the optimal Norwegian strategy is to keep the stock at this critical level and prevent it from migrating out of the Norwegian zone. If the critical level is 2 or less it is optimal for Norway to leave behind slightly more than this (the critical level appears close to 2, judging Figure 4). Hence, if the most likely critical level is 2 and the maximum share others could ever take is about 40 percent, which seems to correspond to the present circumstances, then the optimal non-cooperative strategy for Norway would be to keep the stock slightly above this critical level and allow limited migration of the stock out of her own zone.

Now consider the sustainable catches in the non-cooperative solution. Figure 8 shows how the catches of Norway and the others depend on the maximum share (v) the others would ever have of the stock, given that $\bar{S} = 2$. What is particularly interesting to note is that the catches taken by the others will be greatest if their maximum possible share of the stock is low (between 10 and 20 percent). This is so because if they have a low share, the dominant player (Norway) will have a strong incentive to leave a large stock behind after fishing, because she will reap most of the benefits of this herself. On this the others are able to ride for free. As the maximum stock the others will ever have increases their catches in fact go down, because Norway then has an incentive to fish down the stock in order to reduce its migrations out of the Norwegian zone, and if the maximum share of the others is 70 percent or more the best strategy for Norway is to fish the stock so heavily that it never migrates out of her zone.

THE COOPERATIVE SOLUTION

In a cooperative solution the parties would maximize the sustainable yield, which in this case is 0.9. Agreement would have to be reached on how the gains from this were to be shared. One possible solution is the Nash bargaining solution by which the parties first maximize the gain to be obtained and then share it evenly. The opportunity cost of the cooperative solution is the catch obtained in the non-cooperative play, which clearly is much higher for Norway than for the others. Sharing the gains evenly thus implies

$$\alpha(0.9 - Y_{N,N}) = (1 - \alpha)(0.9 - Y_{N,O})$$

where α is the share of the catch going to Norway and $Y_{N,N}$ and $Y_{N,O}$ are the catches of Norway and the others in the non-cooperative solution. Furthermore, one could ask what the share going to Norway would have to be at the minimum to make her interested in concluding an agreement about cooperation. Clearly her share of the cooperative catch would have to give her at least as great a catch as she would get in the non-cooperative solution. This defines the minimum Norwegian share

$$\min \alpha = Y_{N,N} / 0.9$$

How these two shares depend on the others' maximum share of the resource stock is illustrated in Figure 9. Norway would have to get at least 60 percent of the sustainable yield, and an even split of the gains would give her a share of about 80 percent, but both shares

approach one as the stock becomes more confined to the Norwegian zone. It is worthwhile to note that these shares bear no direct relation to the so-called zonal attachment of the stock, i.e., how much of the stock is to be found inside the two players' economic zones. In the cooperative solution ($S = 5$) the share of the stock in the Norwegian zone (the line u coop) would increase linearly from 70 percent when $v = 0.8$ to 100 percent when $v = 0$, while 97 percent or more of the stock would be in the Norwegian zone in the non-cooperative solution.

CLIMATE CHANGE

One possible effect of a warming of the ocean north and east of Iceland is that the living conditions for the herring would improve in the area. In the 1950s and 60s, as well as earlier, the herring migrated towards the northern coast of Iceland and gave rise to a substantial fishery there. The disappearance of the herring stock from these areas need not have been due solely to overfishing but could also be due to a cooling off of the ocean in this area. In the 1960s the temperature and salinity in these waters dropped precipitously, and at the same time the herring stopped migrating so far west (Malmberg, [1969]). Shortly after the dip both temperature and salinity recovered, although apparently not quite to the previous level (see Malmberg and Jónsson [2002], Figure 2). Nevertheless the herring has not resumed its previous migrations, but it is not unlikely that a further rise in temperature would bring this about.

Three different, but not mutually exclusive, consequences for the herring stock may be envisaged to result from a rising ocean temperature north and east of Iceland. First, the migrations of the Norwegian spring spawning herring could extend further west and make the stock more accessible for exploitation by non-Norwegian fishermen. Secondly, growth conditions could improve so that the maximum stock size would increase. This, in turn, could generate more extensive migrations. Third, local spring spawning herring stocks could emerge. Prior to the herring collapse some herring spawned at Iceland and at the Faeroe Islands, and there are reports of herring spawning off Greenland in the 1930s, a period with a substantially higher temperature in those waters than in later years (Vilhjálmsón, 1997).⁵ These local spawning stocks have long since disappeared, but a summer spawning herring stock remains at Iceland and in a healthy condition.

Here we will concentrate on the implications for the sharing of the herring by a larger carrying capacity of the environment and more extensive migrations, leaving aside the possibility that local spawning stocks would emerge. We model this as doubling of K to 20. From the earlier discussion it may be recalled that the stock was between ten and twenty million tonnes in the 1950s. A $K = 20$ need not, therefore, be at all unrealistic even if it is far beyond what the stock is today.

The effect of this change would be to encourage further migration of herring out of the Norwegian zone. Figure 10 shows that it would still be optimal for Norway in a non-cooperative solution to deplete the stock down to a quite low level, in order to discourage migration out of the Norwegian zone, but the stock left behind after fishing would be higher in this case than with a less productive ocean; Norway would not deplete the herring stock in her zone all the way to the critical level of 2 where it ceases to migrate out of the zone.

⁵ This complex of stocks used to be called Atlanto-Scandian herring.

Another and a more troublesome effect of better conditions in the ocean is that the other parties would probably have to be offered a more lucrative deal in order to ensure their participation in a cooperative solution. The improved conditions in the sea imply that these parties get a larger share of the benefit from the stock left behind by Norway, but they still have no incentives to leave behind any of the stock in their own zone. Figure 11 shows the critical share of the maximum sustainable yield that the other parties would have to get in order to play cooperatively (this share is calculated in a way analogous to $\min \alpha$ above). As the figure shows, this critical share rises substantially as K increases from 10 to 20. The figure also shows the other parties' share ($1 - \alpha$) of the cooperative sustainable catch prior to improved conditions in the ocean (i.e., with $K = 10$) when the gains from cooperation are evenly divided. For some values of v the critical share under the new conditions exceeds the Nash bargaining share in the cooperative solution under the old conditions, implying that the other parties would gain from reverting to the non-cooperative play unless the share they get in the cooperative solution were revised.

Improved conditions in the ocean are therefore likely to put agreements on cooperation under strain, especially because such secular changes in stock growth may be difficult to distinguish from year to year variability, which is substantial and has been ignored here; lasting agreements will have to be concluded on the basis of long term average conditions, but will come under strain as such conditions change. The consequences of such breakdowns could be dramatic. Suppose, for example, that the parties have believed in $K = 10$ for some time but that the others have now concluded that the ocean has become more productive and that they should get a bigger share of the stock. After the breakdown, both parties would be likely to revert to non-cooperative play; Norway would reduce its escapement to something like 2 - 3 million tonnes, the others would catch all they can get, and the stock left behind after fishing would fall by one half or so, from 5 million tonnes to 2 - 3 million tonnes despite increased productivity of the ocean and a greater carrying capacity.

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APPENDIX: THE SURPLUS GROWTH MODEL VERSUS A MULTI-YEAR CLASS APPROACH

As mentioned in the main text, the Norwegian spring spawning herring stock consists of several year classes. It is of interest to check the logistic growth function against the surplus growth that would emerge from a more realistic multi-year class model. For this purpose we look at the yield of an average year class of herring over its life-span. This is the same as the annual yield from a stock in a steady state.

The herring stock consists of sixteen or more year classes. For natural mortality, maturity, and exploitation pattern we use the parameters in Table 3.4.4 in ICES (2003). A logistic growth function was used to express weight at age (w_t), where t denotes age and $t_0 = 3$:

$$w_t = \frac{w_\infty}{\frac{w_\infty - w_{t_0}}{w_{t_0}} e^{-a(t-t_0)} + 1}$$

The parameters of the function were estimated from the weight at age observed for the stock in 2002 (Table 3.2.2.2 in ICES [2003]). The estimation was done by an optimization routine minimizing the sum of squared deviations between the observed weight at age and the calculated weight. The parameters estimated were t_0 , a and w_∞ . Figure A1 shows the values generated by the weight function and the sampled weight at age. The agreement is not poor, but the sampled weight at age follows a somewhat curious pattern, indicating an uneven growth over the life span of the fish. This could be due to the age groups having experienced different growth conditions over their life time. Therefore, a better result could be expected from fitting the growth curve to the weights of individual cohorts. From Table 3.2.2.2 in ICES (2003) it is possible to identify 40 cohorts, starting at the age 3. The parameters of the growth curve did not come out very differently using these data, as can be seen from Table A1. In the following the estimates for the 2002 stock will be used.

Table A1

Value of the parameters of the logistic weight at age function estimated from observations in 2002 and from weights of 40 year classes.

	w_{t_0}	a	w_∞
Stock 2002	0.1702	0.2624	0.4468
40 year classes	0.1837	0.2715	0.4385

Figure A2 shows the development of the weight at age of the 40 said year classes, starting with the year class of 1947 (three year old herring 1950). These diagrams show that the growth of fish can be highly variable; it is not uncommon to see the age-specific weight of a year class drop as it grows older. This could be due to sampling error, but undoubtedly growth conditions vary from year to year. From about 1970, when the year class of 1961 was nine years old, the growth apparently became much more irregular; this was the time at which the herring stock collapsed. In the 1970s and 80s the growth of older year classes apparently was greater than earlier; the year classes gained more in weight and the maximum weight at age

apparently rose. It is tempting to conclude that the growth is density dependent; in this period the stock was extremely small (see Figure 2). From around 1980, when the 1967-71 year classes were ten years old or more, there was a sudden and sharp reversal in growth; weight appears to have declined with age for an extended period. It is less tempting here to invoke density dependence, as the stock growth up until the late 1980s was slow. Since about 1990 the individual growth has been more regular and similar to what it was in the 1950s and 60s, and the weight at age has also been lower than in the 1970s and 80s and about the same as in the 1950s and 60s. Apparently the stock size and behavior is becoming more like what it was in the middle of the previous century, although the migrations are less extensive.

A crucial step in obtaining a surplus growth curve is the link between recruitment of young fish and the size of the spawning stock. As already stated, the recruitment of young fish is highly variable; it can vary by an order of magnitude for the same spawning stock. The reasons for this are not well understood but apparently are related to fluctuations in the marine environment. Figure A3 shows the number of recruits plotted against the spawning stock. A correlation is not apparent.

Table A2

Estimates of a log-linear recruitment function. Data from Table 3.3.3 in ICES (2003).

α	β	R^2
2.3934 (10.90)	1.0053 (6.70)	0.46

A log-linear relationship between the number of recruits and the size of the spawning stock is

$$R_{t+1} = aS_t^\beta$$

where R is recruitment, and S is the size of the spawning stock. Estimation of the log-linear form gave the results in Table A2 (t-values in parenthesis). This implies a linear relationship between spawning stock and recruitment, but we need a concave recruitment function to get meaningful results. The model starts with a given number of recruits (R). Depending on total fish mortality (Z), these recruits produce a certain spawning stock biomass. Call this relationship $f(Z)$. This spawning stock biomass must produce the number of recruits we started with through the recruitment function $R(B)$. We thus seek the solution of

$$B - f(Z)R(B) = 0$$

For a given level of Z , $f(\cdot)$ is a constant, so in order to get a solution $R(B)$ must be non-linear, and for a meaningful solution $R(B)$ must be concave in B . A frequently used concave recruitment function is the Beverton-Holt function:

$$R = \frac{aB}{1 + B/b}$$

A logarithmic form of this function was estimated with an optimization routine minimizing the sum of squared deviations between observed and calculated recruitment. The parameter

values obtained were $a = 11.8$ and $b = 54$. These values differ greatly from the values obtained by Patterson ($a = 32.459$ and $b = 3.044867$), reported in Lindroos and Kaitala (2000, p. 326). Figure A3 shows Beverton-Holt recruitment functions with both sets of parameters, together with the observed recruitment. The function using Patterson's estimates is more curved and appears easier to reconcile with some facts of the fishery, as discussed below.

The surplus growth as a function of the spawning stock biomass⁶ using the Beverton-Holt recruitment function with both sets of parameters is shown in Figure A4. The two curves are remarkably different. The one using the parameters reported above is nearly symmetrical, but implies a rather large maximum biomass (over 30 million tonnes) and a low maximum sustainable yield (less than 650 thousand tonnes). The natural mortality assumed for the zero age group until it reaches the age of three is rather high, or 2.5, while the total mortality of the zero age group until it reaches the age of three, according to Table 3.4.4 in ICES (2003), is 1.8. Using this latter number implies a still greater and less realistic maximum biomass. More seriously, the fishing mortality needed to maximize the sustainable yield is extremely small (about 0.03), and a fishing mortality of 0.09 would be enough to wipe out the spawning stock. This is way below the fishing mortality of recent years, which has been about 0.2 or more.

The sustainable yield curve obtained with Patterson's estimates is markedly skewed to the left. The maximum sustainable yield is markedly higher than in the logistic model while the supporting spawning stock and the maximum spawning stock are both lower. The spawning stock biomass providing maximum sustainable yield is about eight million tonnes, which is close to the actual biomass in recent years. The unexploited biomass (the carrying capacity) is almost 25 million tonnes, which is greater than the stock was in 1950. The maximum sustainable yield is more than twice as high as with the other set of parameters, or 1.5 million tonnes. The fishing mortality needed to produce maximum sustainable yield is 0.25, which is not unreasonable although perhaps a little high. The total mortality assumed for the 0-age group until it reaches the age of three was as in ICES (2003), Table 3.4.4.

While Patterson's estimates can be more easily reconciled with the facts of the herring fishery, it is possible to find parameter values for the Beverton-Holt recruitment function which would do even better in this respect and be more in tune with the logistic model used in the main text. Figure A5 shows the sustainable yield curve emerging with $a = 32$ and $b = 2$. It has maximum for a spawning stock of about 5 million tonnes, like the logistic model, but a larger carrying capacity, because the curve is skewed to the left. It produces a maximum sustainable yield of about 960 thousand tonnes, which is slightly more than the logistic model. The corresponding fishing mortality is slightly above 0.2, which is close the fishing mortality in recent years. Hence it is possible to find parameter values that reasonably reconcile the logistic model and the multi-year class approach. The fundamental problem is, however, what meaning to ascribe to normal, average conditions for a fish stocks influenced by such enormous environmental fluctuations as the Norwegian spring spawning herring apparently is. The logistic equation is not necessarily much worse in that respect than the apparently more realistic multi-year class approach.

⁶ It was assumed that the spawning stock has been exposed to 20 percent of the total mortality, as in Table 3.4.4 in ICES (2003).