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Sharing the Northeast Arctic cod: possible effects of climate change

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Abstract

The Northeast Arctic cod inhabits the exclusive economic zones of Norway and Russia and migrates extensively between these zones. The stock is shared evenly between the two countries, with a small allocation to third countries. Higher temperatures in the Barents Sea and the Norwegian Sea are expected to affect the stock, probably increasing its size and leading to a larger share inhabiting the Russian economic zone. It is also conceivable that some spawning will begin to take place off the coast of Russia in addition to the spawning that now occurs exclusively in Norwegian waters. This paper looks at the implication of this for the division of the stock between the two countries. It is found that a greater presence of the stock in the Russian zone would strengthen rather than weaken the Norwegian bargaining position if the unit cost of fish is not sensitive to the size of the stock. If, on the other hand, the fishing costs are proportional to fishing mortality, Norway's position would be weakened almost on par with the fall in its share of the stock.

The paper uses a Beverton-Holt year class model with a Ricker recruitment function. The recruitment function is hump-shaped, implying that a too large spawning stock is harmful for recruitment. Strong density-dependence in the survival of eggs and larvae is a possible reason for this. It is shown that, for a stock being limited by carrying capacity at the pre-recruit stage rather than the post-recruit stage, one may expect a strongly asymmetric curve for sustainable yield as a function of total biomass. The biomass of an exploited population might possibly exceed the biomass of a pristine population under those circumstances.

Introduction

The Northeast Arctic cod inhabits the Barents Sea and the Norwegian Sea.[1] Its spawning grounds are along the coast of Norway, mainly around the Lofoten Islands. The eggs and larvae are carried by the currents into the Barents Sea and towards Spitzbergen. Being confined to the waters of the continental shelf, the stock is mainly accessible in the Norwegian and the Russian exclusive economic zones, but migrates to some extent out of these zones and into an area known as the Loophole where it is accessible to fishing vessels from other countries. Soon after the exclusive economic zones were established, Norway and the Soviet Union agreed on managing the stock by setting an annual catch quota and to share it evenly among themselves, after making some allowance for third countries which had traditionally fished the stock. In the 1990s fleets from countries not covered by the allocations determined by Norway and Russia fished for cod in the Loophole, but after a few years an agreement was reached with Iceland, the main challenger. Hence it can be said that the stock is under the joint control of Russia and Norway.

In this paper we will ignore the share given to third countries and focus on the sharing between Norway and Russia.[2] The minimum share which either country will agree to depends on how it would fare without an agreement. Neither of the two appears to have a distinct advantage over the other. Norway controls the spawning stock and is thus in a position to control the renewal of the stock, to the extent there is a clear and dependable relationship between the spawning stock and stock renewal. Both countries fish the immature part of the stock, and the mature part outside the spawning season, so with a time lag any Norwegian overfishing of the spawning stock would harm her as well as Russia. Russia fishes the immature stock and the mature stock outside the spawning season, but doing so too heavily would produce a too small spawning stock, which would affect Russia as well as Norway through the impact on stock renewal.

One possible result of a warming of the ocean off the Norwegian coast and the Russian Arctic coast is that the Northeast Arctic cod would establish spawning areas off the Arctic coast of Russia. A similar effect is known to have occurred at Iceland during the ocean warming that occurred in the 1920s and 30s. In this period some spawning of the Icelandic cod occurred north of Iceland, in addition to the traditional areas in the south and west (Vilhjálmsson, 1994). Presumably the larvae from the new spawning areas off the Russian coast would drift into the Barents Sea and become available to some extent in the Norwegian exclusive economic zone. This change in the spawning behavior of the cod is likely to affect the critical shares that Norway and Russia will have to get in order to find a cooperative agreement in their interest. Each country would, as it were, have its own spawning stock, but they would share the immature stock, and the mature stock outside the spawning season, because of its dispersion across both countries' economic zones.

Another possible consequence of the said warming is that the stock might become larger than it has been in recent years, due to a better supply of food and a larger ice-free area in the Barents Sea (Stenevik and Sundby, 2003). Yet another consequence is that the stock might assume a more northeasterly distribution, being available to a greater extent in the Russian

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[1] This stock is also known as Arcto-Norwegian cod.

[2] This share has for some time been fairly constant. In the years 2000-2003 the landings of Northeast Arctic cod by countries other than Russia and Norway were around 13 percent of the total each year (Institute of Marine Research, Bergen, *Havets ressurser 2004*).

economic zone and to a lesser extent in the Norwegian zone. In this paper we examine how these said changes might affect the sharing of the stock.

The benefits to each country are expressed primarily in terms of the quantity of fish caught. This ignores two important economic factors. First, on the revenue side, the price might depend on the volume of catches. Second, on the cost side, the unit cost of fish might differ between the two countries and depend on the size of the stock. This latter effect turns out to be important for the consequences of a changed distribution of the stock between the two countries' economic zones. A third economic consideration, the discounting of future benefits, is not an important one unless one could specify the time path of change towards increased natural productivity and development of new spawning areas, which is certainly not possible.

The model

We use a Beverton-Holt year class model for the fishery. The yield of fish (*Y*) in fishery *i* in fishing season *j* is given by

$$Y_{i,j} = \sum_{k=1}^{K} \left[s_{k,i,j} F_{i,j} \Big/ \left(\sum_{i=1}^{I} s_{k,i,j} F_{i,j} + M \right) \right] N_{k,j} w_k \left\{ 1 - \exp\left[\left(-\sum_{i=1}^{I} s_{k,i,j} F_{i,j} - M \right) \Delta_j \right] \right\}$$

where *s* is a parameter expressing the vulnerability of each age group of fish to fishing, *F* is fishing mortality, *M* is natural mortality, $N_{k,j}$ is the number of fish of age *k* at the beginning of season *j*, w_k is the weight of fish at age *k*, and Δ_j is the length of season *j*. There are two fishing seasons, the spawning season, which covers the first third of the year, and the rest of the year, so that Δ, the length of the fishing season, is one-third and two-thirds, respectively. There are four fisheries, two for each nation. One fishes the immature part of the stock in the spawning season and the entire stock during the rest of the year, while the other fishes the spawning stock in the spawning season. For Russia this last fishery is only present if a warming of the ocean has occurred and spawning grounds have been established off the Russian coast.

The number of fish present in each age group at the beginning of each fishing season is determined by the number of three year old fish and the mortality these fish have suffered since then. The number of three year old fish is determined by the size of the spawning stock through a recruitment function, to be discussed below. The model is a steady-state, deterministic model, showing the yield of fish in a single year in a steady state which may be taken to reflect average conditions.

Weight at age (*w*) is calculated by fitting a logistic function to the observed weight at age for the age groups in the stock in 2002. Data on this, as well as other biological and fishery data used in this paper, are from ICES (2003). The logistic function is

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

The fitting was done by minimizing the sum of squared deviations between observed and calculated weight at age, the parameters to be optimized being w_{t0}, *a* and w_∞. Figure 1 shows the curve fitted and the observed weight at age. Growth over the year is ignored; even if in principle this gives rise to inaccuracy in practice this is limited by the fact that growth is seasonal, occurring mainly in the spring and summer.

Figure 1: Observed wage at age of different age groups of cod in 2002 and a logistic curve fitted to these observations.

The size of the spawning stock depends on the fraction of each age group that has reached sexual maturity and the biomass of fish in each age group. The maturity and selectivity parameters used are shown in Table 1. These values were assumed on the basis of data in ICES (2003). Natural mortality (*M*) was set at 0.2, which appears to be a common assumption.

Table 1: Maturity and selectivity parameters used.

Age	Maturity	Selectivity
3	0	0.01
4	0	0.1
5	0	0.3
6	0.4	0.5
7	0.6	0.7
8	0.9	0.8
9	1	0.9
10+	1	1

To calculate sustainable yield, it is necessary to relate the recruitment of young fish to the spawning stock biomass. ICES (2003) lists data on the spawning stock and recruitment of three year old fish. Figure 2 shows a plot of recruits in year t+3 against the spawning stock in t=0 and an estimated Ricker recruitment function. The parameter of the Ricker function were estimated as (t-values in parenthesis):

$$\ln(R/S) = 0.9907 - 0.001366S$$
$$(6.65) \quad (-4.15)$$

As can be seen from Figure 2, there is enormous variability in recruitment, but it appears that large year classes are less likely to occur if the spawning stock biomass exceeds a certain size, a relationship that the Ricker recruitment function is able to capture. It also appears that the variability of recruitment increases as the spawning stock is reduced. Estimating the parameters of the Beverton-Holt recruitment curve essentially produced a horizontal line which falls to zero as it approaches the *y*-axis. With the observed recruitment being the way it is this is not surprising.

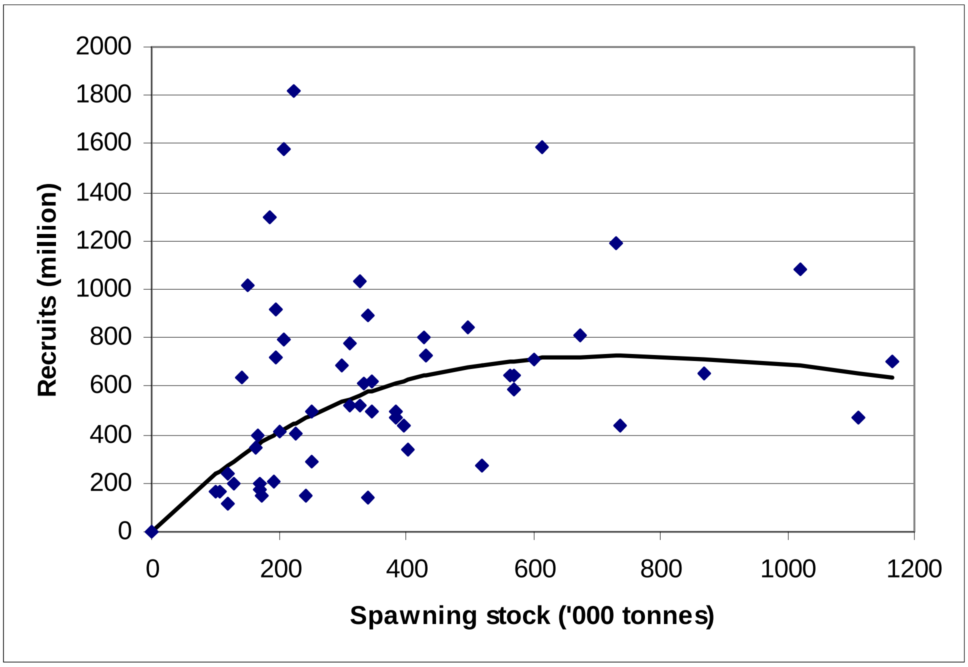

Figure 2: Number of recruits in year *t*+3 against spawning stock in year *t*=0, and an estimated Ricker recruitment curve.

Using the Ricker recruitment function, the logistic growth function, and the vital parameters in Table 1, gives sustainable yield as a function of fishing mortality (*F*), spawning stock biomass, and total biomass, as shown in Figure 3. The sustainable yield as a function of *F* is nearly symmetric, implying a sustainable yield of just over one million tonnes, but obtained at a rather high fishing mortality rate (F = 1.2). This rate is probably not far from the actual rate in recent years, which however has provided a lot less total catch. The reason why this rate is so high is that the selectivity assumed in Table 1 shelters the youngest and fastest growing age groups from being fully hit by the fishing mortality produced by the fishing fleet. According to Figure 3 it would take a fishing mortality of 2.5 to wipe out the stock, which occurs through not permitting any fish to survive until the age of maturity.

The sustainable yield rises quickly as the spawning stock is increased, and then falls rather slowly as the spawning stock increases further. The relationship between sustainable yield and the total biomass of the stock is radically different. Sustainable yield rises almost linearly with the total stock biomass and then falls sharply and bends back slightly. The reason for this is that a large spawning stock is detrimental for recruitment, according to the Ricker curve. The pristine biomass would thus not correspond to the carrying capacity of the environment; by reducing the spawning stock somewhat it would be possible to so improve recruitment as to increase the steady state biomass. It is possible to reconcile this with biological realities by invoking competition for food at the egg and larval stage; if too many eggs and larvae compete, most might get too little to survive, whereas less competition would allow more to survive. The implications of this strange shape of the sustainable yield curve are quite striking. Maximum sustainable yield is in fact attained at about the same biomass as the stock would attain in a pristine equilibrium, the difference being that old and slow-growing age groups would, under exploitation, be replaced by younger age groups that grow faster. The pristine and the maximum sustainable yield stock biomass are both slightly below four million tonnes. This is about equal to the maximum biomass estimated since the Second World War; this maximum was just over four million tonnes in the years 1946-49. This did not, however, represent an unexploited stock, but probably a rather lightly exploited one, since the trawl fisheries were interrupted by the war.

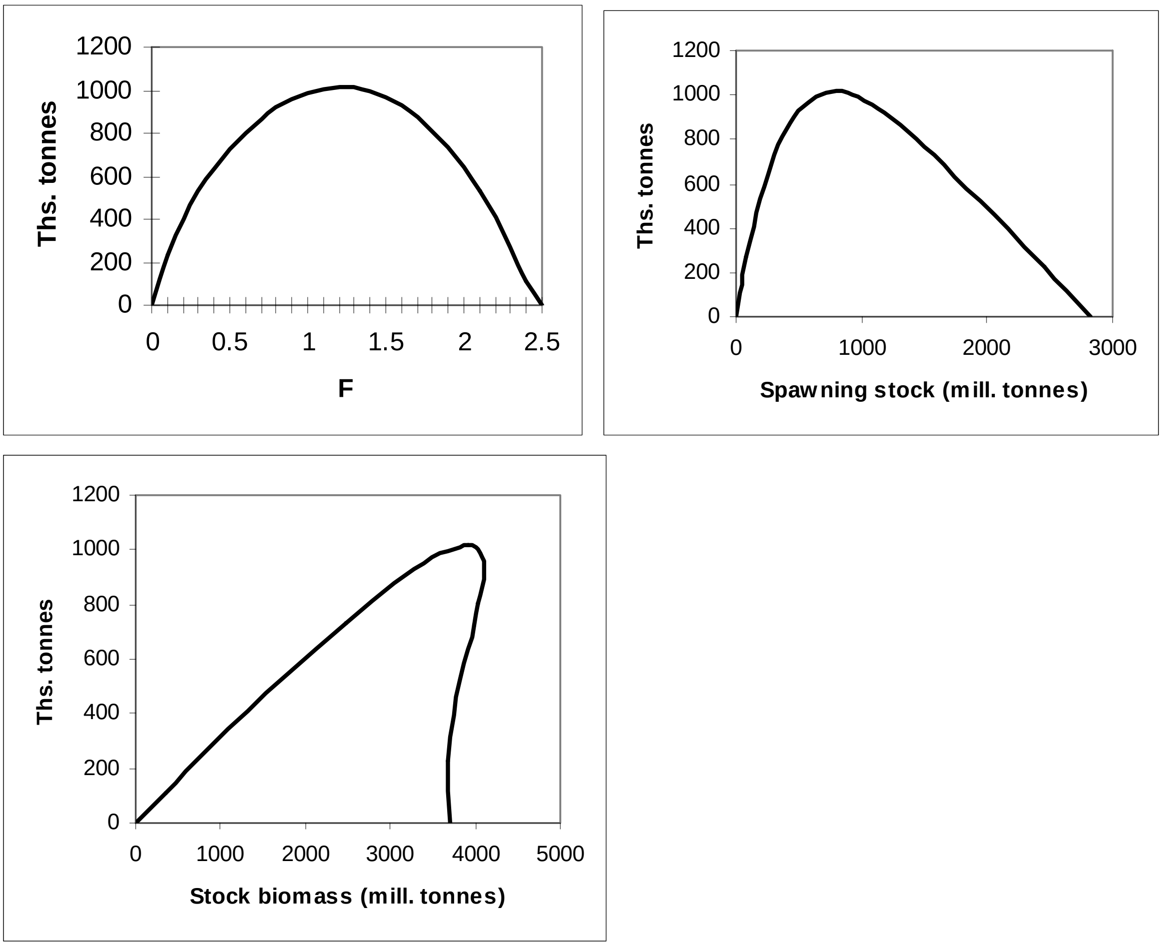

Figure 3: Sustainable yield as a function of fishing mortality (*F*), spawning stock biomass, and total stock biomass.

Norway versus Russia

The mature part of the Northeast Arctic cod stock migrates to the Norwegian coast early in the year to spawn, mainly to the waters around the Lofoten Islands. The spawning process is over by the end of April, after which the stock migrates back into the Norwegian Sea and the Barents Sea. The eggs and larvae drift with the current towards Spitzbergen and into the Barents Sea. The immature age groups migrate towards the northernmost tip of Norway (the coast of Finnmark) early in the year, chasing capelin in search for food, migrating back towards Spitzbergen and the Barents Sea as the spawning migration of capelin is over (most of the capelin die after spawning).

The modeling of these migrations is as follows. First, the year is split into two parts, the first four months and the rest. The mature part of the stock is assumed only to be available for Norway, because of its spawning migration. The immature part of the stock is assumed to be equally available for Norway and Russia in this period. In the next period the spawning stock is assumed to have migrated back into the Norwegian Sea and the Barents Sea and to be equally available for both countries. The share of the stock available in each country's economic zone varies from year to year, according to climatic conditions, and it is possible that more than half of the stock is available in the Norwegian zone on the average, but here we shall assume an even distribution between the zones.

The model looks at long term equilibria in the fishery, or what is equivalent, at the yield from one year class of fish in equilibrium. The spawning stock biomass is determined as the stock remaining half way through the first fishing season (the spawning season), because all fish do not spawn at the same time, and assuming they all do so at the beginning of the period would ensure the survival of the stock even if the spawning stock would be wiped out almost immediately at the beginning of the period.

The two parties, Russia and Norway, are assumed to maximize the sustainable yield from their cod fisheries. Their strategies involve setting the appropriate level of fishing mortalities for the stock. Norway has two strategic variables, F_{Na} and F_{Nb}. F_{Na} is the fishing mortality for the mature stock in the first period of the year, which is only available in the Norwegian zone because of the spawning migrations. F_{Nb} is the fishing mortality for the rest of the stock that is available in its zone the first part of the year, and for the whole stock available in the Norwegian zone in the second part of the year. Russia, however, has only one strategic variable, F_R, which is the fishing mortality of the stock available in the Russian zone in both parts of the year, which excludes the spawning part of the stock in the first part of the year. The selectivity of both countries' fisheries is assumed to be the same and as in Table 1 above. Table 2 shows the payoffs for the said fishing strategies.

Table 2: Payoffs from optimizing the available fishing strategies.

	F_{Na}	F_{Nb}	F_R	Yield Norway	Yield Russia	Total
Maximum yield	6.5	0	0	1204.9	0	1204.9
Nash equilibrium	0	1.71	1.71	469.4	469.4	938.8
Maximum equal yield to each (a)	0	1.4	1.4	497.0	497.0	994.0
Maximum equal yield to each (b)	3.071	0	1.52	543.0	543.0	1086.0

From the first row in Table 2 we see that, in order to maximize the sustainable yield, only the mature part of the stock should be fished. The reason for this lies in the greater selectivity this affords of mature age groups; fishing these age groups selectively better utilizes the growth potential of the stock than fishing the younger age groups as well. The implied fishing mortality is quite high, although not as high as it appears to be, since it is only applied for one-third of the year and thus reduces to slightly above 2. The practical relevance of this is limited because it would imply catches only during the first third of the year, and it would give nothing to Russia unless she were allowed to send her boats into the Norwegian economic zone and catch her fish there.

Turning then to the non-cooperative solution (the Nash equilibrium), it would be in the interest of Norway not to fish on the spawning migration of the fish. With Russia fishing the stock in her zone heavily, the mature age groups would be heavily depleted, and Norway would in her own interest have to spare these age groups in order to ensure sufficient recruitment of young fish. In the Nash equilibrium, both nations fish with a fishing mortality of 1.71 in their respective zones, with the total yield being about 80% of the maximum sustainable yield (row one).

Maximizing the sustainable yield for both parties, given that each should get an equal share, can be accomplished either by having both fish with the same fishing mortality in each party's zone and sparing the spawning migration, or by having Norway fish on the spawning migration and Russia fishing on the stock in her zone. It would not be optimal to have Norway fish both on the spawning migration and the rest of the stock in her zone, and on all the stock in her zone in the latter period. The results of both strategies are shown in rows three and four in Table 2. It turns out that the sustainable yield is maximized with Norway fishing on the spawning migration and Russia fishing on the stock in her own zone. Russia would fish with a fishing mortality of 1.52, and Norway would fish the spawning stock with a fishing mortality of 3.071, which however would only apply in the first third of the year. This results in a sustainable yield that is almost ten percent greater than with sparing the spawning migration and having both countries fish with a fishing mortality of 1.4 in the respective zone.

The sustainable yield when the spawning migration is spared and each country fishes with a fishing mortality of 1.4 is about five percent greater than in the Nash equilibrium. Hence the loss involved in playing non-cooperatively is not great. By having Norway fish on the spawning migration and nothing else the total sustainable yield would be almost 17 percent higher than in the Nash equilibrium, but as already stated it is unrealistic to think that a total concentration of fish landings to the first third of the year would be optimal.

Two spawning stocks

Now suppose that the growth conditions in the Barents Sea improve because of higher temperatures. One possible consequence of this is that new spawning grounds will be established on the Arctic coast of Russia and perhaps on the coast of Novaya Zemlya. Such colonization was observed for the Icelandic cod stock in the warm period 1920-1940; a part of the stock migrated to Greenland, and new spawning grounds were established on the North coast of Iceland (Vilhjálmsson, 1997). A warmer ocean climate may also be expected to increase the size of the stock. A warming of the ocean might induce the *Calanus Finnmarchicus*, a small animal of great importance as a food source for cod, to colonize new areas in the Barents Sea and improve the growth conditions for the cod stock (Stenevik and Sundby, 2003). Let us assume, for contrast, that these changes are so dramatic that the total stock will be doubled, and that the new spawning component in the Russian economic zone will be of the same size as the one in the Norwegian zone. After spawning the stock will migrate into the Norwegian Sea and the Barents Sea. We continue to assume that one half of each stock will be available for each of the two countries. This may be unrealistic; it is perhaps more likely that the Russian component will mainly be available in the Russian zone and vice versa for the Norwegian component.

Table 3 shows the results of four fishing strategies. As before, the total catch would be maximized by fishing only the mature part of the stock. The interesting thing to note here is that this would now be a Nash equilibrium. The best response by Russia to Norway choosing to fish only the spawning stock in her own zone would be to do likewise. This is clear from the last row of Table 3. Russia would not have anything to gain from fishing the immature stock. While this would allow Russia to fish on the Norwegian stock component, which would enormously reduce the catches taken by Norway, the gain from this would not outweigh the loss Russia would suffer from decimating her own spawning stock. The same applies, mutatis mutandis, to Norway. The critical point here is the symmetry between the two countries, i.e., that both stocks distribute themselves equally between the two countries' economic zones and are equally big.

Table 3: Payoffs from optimizing the available fishing strategies when the stock doubles and there is a spawning stock off the coast of Russia.

	F_{Na}	F_{Ra}	F_{Nb}	F_{Rb}	**Yield Norway**	**Yield Russia**
Maximum Catch	6.5	6.5	0	0	1204.9	1204.9
Maximum catch if no fishing of spawners	0	0	1.4	1.4	994.0	994.0
Nash equilibrium	0	0	1.71	1.71	938.8	938.8
Nash equilibrium if $F_{Ra} = 0$	6.5	0	0	2.2	279.9	1128.0

As already mentioned, fishing only the spawning migrations would imply an extremely seasonal fishery and may not, therefore, be the best thing to do even if it would result in the largest catch volume. If the entire stock is to be fished, the best thing to do is to spare the spawning runs and fish the mature part of the stock only when it is mixed with the remainder of the stock. The maximum catch would be obtained with a fishing mortality of $F = 1.4$, same as before. But this is not a Nash equilibrium; if one country applies this fishing mortality the other one would gain by fishing harder still. The Nash equilibrium strategy is exactly the same as before, F = 1.71, but with twice as large catch due to the assumption of stock doubling.

More of the stock to Russia

One possible effect of a warmer ocean climate is that the cod stock would migrate further north and east into the Barents Sea without necessarily getting any bigger or establishing new spawning areas off the coast of Russia. This would mean that more of the stock would be available in the Russian economic zone.

Table 4 shows how the Nash equilibrium solution depends on how the stock is distributed between the Norwegian and the Russian zones, with the spawning being assumed to take place exclusively in the Norwegian zone. The results are surprising and counterintuitive.

Contrary to what one would expect, having a smaller share of the stock in fact strengthens the bargaining position of Norway up to a point. The table shows that the catches taken by Norway increase as her share of the stock falls from 50% to 20%. In order to accept the cooperative solution, Norway would have to be offered a share of that solution giving her at least the same catch volume as she would obtain in the non-cooperative solution. This share, and the corresponding minimum share for Russia, is shown in the table. We see that the minimum share to be offered to Norway increases from 47% when she shares the stock evenly to 53% when she has only 20% of the stock, while the critical share to be offered to Russia falls from 47% to 38%. This counterintuitive result is a variation on a theme explored elsewhere (Hannesson, 2004), which established that there is not necessarily any relationship between the share of a fish stock available in a country's economic zone and the share it needs to be offered of the total catch in a cooperative solution. Needless to say, there is a limit to how far having a smaller share of the stock will strengthen one's bargaining position; in Table 4 we see that as the Norwegian share falls from 20% to 10%, her catches fall as well, and her bargaining position will be weakened.

Table 4: Nash equilibrium solutions for different distributions of the Northeast Arctic cod.

$F_{N,a}$	F_{Nb}	F_{Rb}	**Norway's share of stock**	**Norway's minimum share of catch in cooperative solution**	**Russia's minimum share of catch in cooperative solution**	**Catch Norway**	**Catch Russia**	**Total catch**
0	1.71	1.71	0.5	0.47	0.47	469.4	469.4	938.8
0	2.53	1.31	0.4	0.48	0.45	479.0	451.5	930.5
0	5.1	1.0	0.3	0.52	0.42	513.1	420.5	933.7
0	130	0.89	0.2	0.53	0.38	526.1	378.9	905.0
0	$\rightarrow \infty$	1.11	0.1	0.34	0.64	337.8	637.7	975.4

The explanation for the counterintuitive result that Norway's total catch increases when the attachment of the cod stock to her zone falls, strengthening her bargaining position, is that the conservation incentive becomes weaker. The consequences of overfishing the stock in the Norwegian zone will be borne disproportionately by Russia if she has a larger share of the stock. The conservation incentives for Russia become stronger as her share of the stock increases, and Norway is able to benefit from this. A critical assumption here is that the fish are assumed always to redistribute themselves between the zones at the beginning of each year, not just the mature part which migrates to the spawning grounds off the Norwegian coast but also the immature part. To the extent the immature year classes remain in each country's zone once they have drifted there the above results would be weakened, with Norway suffering a greater loss of catch in the future as a consequence of heavy fishing in her zone. It is not entirely unrealistic to suppose that the young year classes will redistribute themselves in the way mentioned; these year classes are known to chase capelin to its spawning grounds off the northernmost coast of Norway. On the other hand, should the capelin begin to spawn off the Russian coast as a result of a warmer ocean climate this migration would be diverted, and should the capelin begin to spawn exclusively off the coast of Russia we might get migrations of young cod out of the Norwegian zone and into the Russian zone. This would obviously weaken the position of Norway.

Taking fishing costs into account would weaken the above counterintuitive results. From Table 4 we see that the fishing mortality in the Norwegian zone increases dramatically as her share of the stock falls, and as her share falls to 20% or less she would in effect be scooping up all the fish available in her zone each year, banking on the fact that it will always be replenished from the Russian zone. It has already been mentioned that such extensive migrations could be unrealistic. Furthermore, the very high fishing mortalities needed would be associated with high costs, but how high would depend on how sensitive the catch per unit of effort is to the size of the stock. This, and the fact that such high fishing mortalities would imply a heavy concentration of catches in the beginning of the year, would make this fishing strategy unattractive, which in turn would weaken the bargaining position of Norway as her share of the stock goes down. Nevertheless, the example serves to underline that the bargaining position of Norway need not weaken even if her share of the stock falls somewhat; it might in fact be strengthened up to a point.

Yet another angle on the result discussed here is that the present 50-50 share agreed between Norway and the Soviet Union in the late 1970s might in fact be in the interest of both parties, even if more than half of the stock is usually available in the Norwegian zone. It is known that at least in some years with low ocean temperatures the stock has had a westerly distribution, so that more of it has been available in the Norwegian zone. This might be thought of as strengthening the Norwegian bargaining position, but that is not necessarily so, according to the above results. It may very well be that the 50-50 distribution was not arrived at on the basis on any "zonal attachment" of the stock, but whatever the arguments behind the said distribution, it may very well have been just about right when looked at from the point of view of strategic choices.

Costs and the effects of changed distribution

As indicated in the previous section, it is likely that cost considerations would prevent Norway from increasing its catches as her share of the stock shrinks. This is illustrated by the results in Table 5. Here it is assumed that the cost of fishing is proportional to fishing mortality, which would be the case if costs are proportional to fishing effort and the stock is always evenly distributed over a given area. The cost is assumed to be equal for both countries and implies a resource rent of about 40 percent in the cooperative solution.

Table 5: Cooperative solution and two Nash equilibria when fishing costs are 300 per unit of *F*.

	F_{Na}	F_{Nb}	F_R	**Catch Norway**	**Norway's share of stock**	**Catch Russia**	**Total**	**Profit Norway**	**Profit Russia**
Cooperative solution	0	0.76	0.76	398.5	0.5	398.5	797.1	170.5	170.5
Nash equilibrium	0	0.94	0.94	445.3	0.5	445.3	890.5	163.3	163.3
Nash equilibrium	0	1.04	0.88	385.7	0.4	506.0	891.7	136.1	189.2
Nash equilibrium	0	1.16	0.82	317.7	0.3	562.2	879.9	108.9	217.8

Since fishing costs rise with fishing mortality (*F*), it is not worthwhile to catch as much fish as when costs are either ignored or not related to *F* at all, as in the previous tables.[3] The optimal sustainable yield when the spawning stock is not fished falls from almost one million tonnes

[3] As elsewhere in this paper, discounting is ignored.

to about 800,000, and the corresponding fishing mortality falls by almost one half, or from 1.41 to 0.76. The Nash equilibrium implies a substantial increase in sustainable yield, or almost 100,000 tonnes, but only about 4 percent less profit than the cooperative solution, while the fishing mortality increases from 0.76 to 0.94. Hence, under this cost assumption the waste involved in the Nash equilibrium is not very great, and the exploitation rate in the Nash equilibrium would still be lower than that which would maximize the sustainable yield.

The last two rows of Table 5 show what happens if the Norwegian share of the stock shrinks from 50 to 40 or 30 percent, respectively.[4] This entices Norway to increase the fishing mortality in her zone from 0.94 to 1.04 or 1.16, which is in tune with the weakening of the conservation incentives discussed above. But this is nowhere near enough to maintain her share of the total catch; this falls to 43 or 36 percent. This is less than the fall in her share of the stock, but nowhere enough to maintain her 50 percent share as in the examples without cost. The cost associated with raising the fishing mortality as required for maintaining her share of the catch is simply not worth while, so in this case Norway would clearly suffer a disadvantage from having a smaller share of the stock. The profit that she realizes in the Nash equilibrium is close to 42 or 33 percent of the total profits in the cooperative solution, so in this case her critical share of the catches and profits in the cooperative solution would be rather close to the share of the stock in her zone.

As the share of the stock in the Norwegian zone declines, it would become more attractive for Norway to fish on the spawning migration, eventually in conjunction with fishing the immature part in her own zone. How attractive this would be depends on the cost of fishing in the spawning migration, which need not be the same as for fishing the immature part of the stock and the mature part outside the spawning season.

Conclusion

Whether or not we are faced with a warming trend in the waters of the Norwegian Sea and the Barents Sea is still too early to tell. Temperature fluctuations on a decadal scale are known to have occurred in these areas for a long time. These fluctuations have had an impact on the growth and distribution of the Northeast Arctic cod. A warming trend can be expected to have similar but lasting effects, and perhaps it may bring the ecosystem of the said areas across critical thresholds beyond which they enter new regimes characterized by major changes in species composition and stock sizes. In any event, the changes in migrations and distribution of the Northeast Arctic cod, currently the most valuable fish stock in this region, is likely to affect the relative bargaining strength of the two countries sharing this stock, Norway and Russia. Not surprisingly, it is primarily the distribution of the stock between the Russian and Norwegian economic zones which would alter the relative bargaining strength of the two countries. Contrary to expectation, the country experiencing a decline in the share of the stock in its economic zone need not see its bargaining position eroded, because of a simultaneous weakening in its conservation incentives. This will happen if the unit cost of fish is unrelated to the size of the stock. If on the other hand the cost of fishing is proportional to fishing

[4] Note that the cost per unit of F has been adjusted by the factor $\alpha/0.5$ and $(1-\alpha)/0.5$, where α is Norway's share of the stock. The reason is that, in the model, the stock is assumed to stay within the zones of Norway versus Russia for the entire year, and to redistribute itself between the two zones at random at the end of the year. This ensures that if the fish available in the Norwegian zone falls by x percent so that the catch, for any given F, falls by x percent, the cost will also fall by x percent. Hence the change in the distribution of the stock between the Norwegian and Russian zone imposes no cost disadvantage on Norway other than she would have to fish harder to maintain any given catch.

mortality it will be too costly for the country experiencing a declining share of the stock to counteract this by increasing its catches. In this latter case, which probably is the more realistic one, a smaller share of the stock in a country's zone will mean a disadvantage in the bargaining over shares of a total catch quota. In any event, major changes in ocean climate are likely to put existing agreements on shared fish stocks such as the Northeast Arctic cod under stress.

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