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INCENTIVE COMPATIBILITY OF FISH-SHARING AGREEMENTS: THREE STOCK MIGRATION MODELS

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Abstract

Shared fish stocks are such as migrate across borders between different countries' exclusive economic zones. This paper discusses the incentive compatibility of fish-sharing agreements based on the zonal attachment of such stocks. Three types of migrations are considered: (i) a common stock that grows and reproduces and is then distributed in given proportions between two countries' zones at the beginning of each fishing season; (ii) sub-stocks that breed and grow independently in their separate zones but spill over between zones according to relative abundance; (iii) a stock that grows and breeds in one country's zone but migrates into the zone of another if it exceeds a certain size. It is shown that in all these cases the minor partner in a fish-sharing agreement may not have an incentive to cooperate unless he gets a larger share of the cooperative profits than corresponds to his share of the stock. This is particularly likely to happen when the unit cost of fish does not depend on the stock. An exception could occur if stock migration depends on the stock level; the major partner could then keep the entire stock by fishing it down to a critical level.

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INTRODUCTION

In the 1970s, while the Third UN Conference on the Law of the Sea was still ongoing, the conference endorsed the concept of a 200-mile exclusive economic zone (EEZ). In the latter half of the 1970s many countries world wide established such zones. This turned fish stocks that migrate between these zones into a shared property of two or more countries. Successful management of such “transboundary” stocks requires that the countries involved agree on how the stocks are to be shared and managed. In the late 1970s Norway and the European Union agreed to share seven transboundary stocks in the North Sea according to the “zonal attachment” of each stock.[1] The stocks are managed by setting an overall catch quota, which is then divided between Norway and the European Union as determined by the zonal attachment.

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 one country while not becoming fishable until they have moved into the zone of another. Other types of fish may feed in the zone of one country but fishable mainly in the zone of another. 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]).

With the exception of North Sea herring, the sharing agreement for the North Sea stocks has held up well. Like other herring stocks, the North Sea herring stock fluctuates considerably in size because of environmental factors, changing 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 it was being offered on the basis of the previous zonal attachment of the stock. For some time no agreement was in force, 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), the more the larger the stock is.

There have been other and less successful attempts to apply the zonal attachment principle. No agreement has yet been obtained for blue whiting and mackerel in the Northeast Atlantic, and an agreement on sharing the Norwegian spring spawning herring fell apart in 2003. A complicating factor is that these stocks migrate into the high seas outside the exclusive economic zone of any country where no single country has jurisdiction and international agreements are difficult to enforce. But there are other problems with the zonal attachment principle. It may appear reasonable and fair, but there is no a priori reason why it should be compatible with the incentives of the individual parties. In this paper it is shown that countries with a minor share in a stock could be better off by exploiting the fish in their own zone as they best see fit than by cooperating on the basis of the zonal attachment principle. This is

[1] These stocks are cod, haddock, saithe, plaice, whiting, sprat and herring (Engesæter [1993]). On the concept of zonal attachment, see ICES (1978) and Engesæter (1993).

particularly likely to happen for stocks where the unit cost of fish is only weakly related to the size of the exploited stock. This apparently is the case for the said stocks for which no agreement is in force.[2] The reason could be the aforementioned incentive problems, rather than the fact that the stocks involved are partly accessible on the high seas. What is perhaps more surprising is that the sharing agreements for the stocks in the North Sea have held up so well despite being based on the principle of zonal attachment.

In this paper we will use a discrete time version of the classic logistic model for the growth and reproduction of the stock. As to how to model stock migrations, many avenues are open, reflecting different realities. A fish stock may grow and breed as a unit and then be diffused in a certain way among different national zones. A variant of this is the split-stream model (McKelvey, Sandal and Steinshamn, 2002, 2003). Another possibility is that sub-stocks grow and breed independently in separate locations confined to the zones of different countries but migrate between zones. Such migrations might depend on relative stock abundances in the two locations, or the stock may be basically confined to one location and then spill over to another if it exceeds a certain level. We will consider three migration models that focus on these possibilities.

There are aspects of fish migrations that are not covered by the models to be presented. One is randomness in stock migrations and, hence, in zonal attachments. Such randomness would seem to increase the likelihood of controversies arising over the sharing of fish stocks. Another issue is age-dependent migration, such as young fish being recruited from Country A's zone into Country B's zone, from where they would migrate back into Country A's zone as they grow older. This problem cannot be dealt with by a general biomass model such as the one used here. We leave these issues for future research and concentrate here on the incentive-compatibility of the zonal attachment principle on what is likely to be its most favorable terms. The analysis applies game theory, contrasting a non-cooperative Nash equilibrium with a cooperative, or globally optimal, solution. This is a common approach to the problem of shared fish stocks (see, for example, Hannesson [1997], Kennedy [2003], and a special issue of Marine Resource Economics edited by Bjørndal [2000]). The zonal attachment principle has not, however, been dealt with in the literature. The purpose of the present paper is to fill that hole in the literature.

THREE MODELS OF MIGRATIONS

It is possible to model the migrations of fish stocks between the EEZs of different states, or between EEZs and the high seas, in various ways. While ultimately an empirical matter where each case has its own specific features, what we are concerned with here are generic models of some generality. Here we offer three stylized models. In some situations one of these might obtain in a reasonably pure form. The three types of migrations we have in mind are the following:

a) **Common reproductive stock** In this case the stock occurs in two countries' EEZ (or in one country's EEZ and on the high seas). The growth of the stock depends on the sum total of the sub-stocks left after fishing in the two zones. At the beginning of the next fishing season the new stock distributes itself in a given fashion between the two

[2] Bjørndal (1987) has estimated a production function for herring that implies a weak dependence of the unit cost of fish on the size of the stock. This is due to fishing on fish aggregations that are relatively easily detected. This also characterizes the blue whiting fishery.

zones. The split-stream model used by McKelvey, Sandal and Steinshamn (2002, 2003) is of this kind.

b) **Pure spillover** In this case the growth and reproduction of the sub-stocks in each country's EEZ depend on the amount of fish left after fishing, but the fish migrate between the zones, the net migration depending on the relative density of the sub-stocks in the two zones.

c) **Spillover with a critical threshold** Here the stock is confined to one country's EEZ unless it exceeds some critical level. The fish that migrate out of the zone return to breed and grow. Hence, growth and reproduction depend on the sum total of the stocks left behind in the two areas, as in the split stream model.

The specifications of the three models are as follows:

Common reproductive stock

(1a) $$X_{1,t+1} = \beta\left[\left(S_{1,t}+S_{2,t}\right)+r\left(S_{1,t}+S_{2,t}\right)\left[1-\left(S_{1,t}+S_{2,t}\right)\right]\right]$$

(1b) $$X_{2,t+1} = (1-\beta)\left[\left(S_{1,t}+S_{2,t}\right)+r\left(S_{1,t}+S_{2,t}\right)\left[1-\left(S_{1,t}+S_{2,t}\right)\right]\right]$$

There are two countries, 1 and 2. X denotes the stock available at the beginning of each period. The growth depends on the stocks (S) left behind by both countries after the fishing in each period is over. Country 1 always gets the share β of the emerging stock while Country 2 gets the rest. A case in point could be the Arcto-Norwegian cod which spawns in the Lofoten area. The eggs and fry are carried northwards by the currents and distributed between the Norwegian and Russian EEZs. This very simple model does not capture all aspects of this fishery, however, nor is it meant to. These fish take years to mature, and in between the sub-stocks grow within their respective zones. Furthermore, the distribution of the emerging cohorts of fish is not constant over time but depends on environmental factors.

Pure spillover

In this case it is assumed that the sub-stocks grow independently of one another but spill over from one EEZ to another, depending on the density of the sub-stocks in the two areas:

(2a) $$\begin{aligned} X_{1,t+1} &= S_1 + rS_1\left(1-\frac{S_{1,t}}{\beta}\right) \\ &+\delta\left[\frac{S_2+rS_2\left(1-S_2/(1-\beta)\right)}{1-\beta}-\frac{S_1+rS_1\left(1-S_1/\beta\right)}{\beta}\right] \end{aligned}$$

(2b) $$\begin{aligned} X_{2,t+1} &= S_2 + rS_2\left(1-\frac{S_{2,t}}{1-\beta}\right) \\ &+\delta\left[\frac{S_1+rS_1\left(1-S_1/\beta\right)}{\beta}-\frac{S_2+rS_2\left(1-S_2/(1-\beta)\right)}{1-\beta}\right] \end{aligned}$$

The first part of these equations is the surplus growth function (plus the stock left over in the previous fishing period). Here the parameter β denotes the relative size of the EEZ of one of the parties, wile both EEZs sum to unity. If both areas are equally productive in relative terms, the carrying capacities will be β and 1 - β, respectively, of a total carrying capacity of one, as assumed for the common reproductive stock.

The second term accounts for the migrations of the sub-stocks between areas. The net migration is assumed to depend on the relative densities of the stocks being reproduced in the two areas. If the density of the stock emerging at the beginning of each fishing period is, say, greater in Area 1 than in Area 2, then some of the emerging stock will spill over into Area 2. To get density, we divide the size of the sub-stocks by the size of the area. The intensity of the flow increases as the difference in stock density in the two areas increases. In equilibrium without fishing there would be no net flow between the areas.

There are many real world examples of stocks migrating between the EEZs of different countries. One is the Arcto-Norwegian cod, already mentioned, others are Atlantic mackerel and herring, which also migrate into the high seas. These migrations are known to be driven by the availability of food. There is not to our knowledge any firm evidence as to whether these migrations are affected by relative densities in different EEZs, so this must be regarded as an interesting and plausible hypothesis rather than an empirically verified fact; if the stock in one area is much smaller than in an adjacent area, relative to carrying capacity, the availability of food would presumably be greater in the area with a small stock.

Spillover with a critical threshold

In this case the growth functions are

$$\text{(3a)} \quad \begin{aligned} X_{1,t+1} &= S_1 + S_2 + r\left(S_1 + S_2\right)\left[1 - \left(S_1 + S_2\right)\right] \\ &- \max\left\{0, \delta\left[S_1 + S_2 + r\left(S_1 + S_2\right)\left[1 - \left(S_1 + S_2\right)\right] - \bar{S}\right]\right\} \end{aligned}$$

$$\text{(3b)} \quad X_{2,t+1} = \max\left\{0, \delta\left[S_1 + S_2 + r\left(S_1 + S_2\right)\left[1 - \left(S_1 + S_2\right)\right] - \bar{S}\right]\right\}$$

In this case, the stock migrates out of the EEZ of Country 1 only if the emerging stock at the beginning of the fishing period exceeds a critical level $\bar{S}$. The stock left behind in Country 2's zone migrates back to Country 1's EEZ where the entire stock grows and reproduces. An example is the Norwegian spring spawning herring, which migrates out of the Norwegian EEZs and into the high seas as well as the EEZs of the neighboring countries. In recent times the stock has returned to the Norwegian zone to winter and to reproduce but is known to have wintered and reproduced in other areas in the early and mid-20th century.[3]

STOCK-INDEPENDENT UNIT COSTS

We shall contrast a cooperative solution for the management of the stock with a non-cooperative one where each country optimizes its own profits. The cooperative solution will be taken to be maximization of the sum total of profits. The cooperative solution will be

[3] For a review of the migrations of this stock, see Sissener and Bjørndal (2004).

viable if both players' shares of the cooperative profit are greater or equal to what they could get in the non-cooperative solution. That is

(4a) $\alpha\pi^{o} \geq \pi_{1}^{*}$

(4b) $(1-\alpha)\pi^{o} \geq \pi_{2}^{*}$

where α is the major player's share in the cooperative profits (π^o) and π_i^* denotes the profit obtained by player *i* in the non-cooperative solution. Player 1 is the major player, in the sense that he has the largest share of the stock (β > ½). To be incentive compatible, (4) must hold for a sharing agreement. The lead question in the following is how the incentive compatible α and 1 - α compare with β and 1 - β, the zonal attachment parameters. For reasons that will become clear, we focus on the shares of the minor player.

As to the non-cooperative solution, the question arises what the strategic variable is. There are at least three candidates; fishing effort, the amount of fish caught, and the stock level left behind after fishing. We will use the last of the three as a strategic variable. Implicitly this assumes that there is sufficient fleet capacity to fish down the stock to whatever level desired. Each player therefore sets its optimal stock level for a given level selected by the other party. The non-cooperative solution consists of mutually consistent solutions for the two players. Catch as a strategic variable would primarily be of interest if we wanted to take into account how price depends on quantity. We disregard this issue and assume a given price independent of quantity, set equal to one. We shall begin by examining the case where the cost of fishing can be ignored. This essentially amounts to saying that the cost per unit of fish caught is a constant. If the price is also constant, we can account for the costs simply by deducting the unit cost from the gross raw fish price. It is convenient to refer to this as the costless case, even if it is a bit misleading.

In what follows we shall ignore time discounting. While it is well known that time discounting affects the optimal standing stock,[4] it is not critical for whether or not a cooperative solution to the fish-sharing problem should be based on "zonal attachment" of the stock, which is the question at hand.[5]

Common reproductive stock

For comparison with the non-cooperative solution, note that the maximization of sustainable profits from both stocks at a constant price implies maximizing $X_1 + X_2 - S_1 - S_2$. Using Equations (1) and the first order condition we get

(5) $S_1^o + S_2^o = 1/2$

With the specification we have used, it would not matter in this case where the stock is left to grow; it is the sum of sub-stocks left in the two areas that counts.

Now consider the non-cooperative case. The parties maximize $X_1 - S_1$ and $X_2 - S_2$, respectively. From (1) we have the first order conditions

[4] See, for example, Clark (1976).
[5] For an analysis which takes the discount rate into account, see Hannesson (2004).

(6a) $\beta\left[1+r-2r\left(S_1^*+\bar{S}_2\right)\right]-1=0$

(6b) $\left(1-\beta\right)\left[1+r-2r\left(\bar{S}_1+S_2^*\right)\right]-1=0$

where the asterisks denote the optimal solutions in the non-cooperative case, and bar over a variable that it is taken as given by the player. These equations cannot be satisfied simultaneously, except for β = ½. The "minor" player, i.e., the one who gets the smaller share of the returning stock, will never have an incentive to leave anything behind; it is the other player who gets the largest share of the gain from any fish left by the minor player to grow and to reproduce. Furthermore, the minor player will free ride on the conservation efforts of the major player, who has a stronger incentive to conserve. But we are not guaranteed that the major player will have an incentive to leave anything behind either. From (6a), the condition for $S_1^* > 0$, given that $S_2^* = 0$, is $r > 1/\beta - 1 \geq 1$ ($\beta \geq$ ½, because it is the share of the major player). For example, if r = 0.5, the share the major player gets from the emerging stock would have to be greater than two thirds. For any fish left in the sea for growth and reproduction, the major player loses a share (1 - β) to the other player. The share he gets of the maximum incremental stock growth is $r\beta$. Therefore, if leaving the last fish behind is not to result in a loss for the major player, we must have $r\beta$ - (1 - β) > 0, which again gives us $r > 1/\beta - 1$.

This example illustrates how unit costs of fish that are independent of the stock increase the risk of extinction in a competitive fishery. Here it could happen with just two independent agents that fail to coordinate their actions, unless one of them has a sufficiently large share of the fishery. As we will see later, this does not happen with stock-dependent unit costs. It is also much less likely to happen under the alternative specifications of the fish migrations.

How large a share of the profits of the cooperative solution would the minor party have to be offered in order to cooperate? Since S_2^* = 0, Equation (6a) gives (provided r (or β) is sufficiently large):

(7) $$S_1^* = \frac{\beta\left(1+r\right)-1}{2r\beta}$$

Using (1) and (5) to calculate the profits in the cooperative and non-cooperative solution, we get from (4b)

(8) $$\left(1-\alpha\right)r\left(1-\frac{1}{2}\right) \geq \left(1-\beta\right)\left[S_1^*\left(1+r\right)\left(1-S_1^*\right)\right]$$

from which, using (7), we can calculate the critical share (1 - α). Obviously, this is not equal to the stock share (1 - β). The critical share as a function of β is shown in Figure 1 together with the share of the stock, for r = 1. We see that the minor player has to be offered a share of the catch that is greater than his share of the stock, unless the latter is close to one half. In fact, the minor player's profit increases as the major player's share of the stock rises from ½ up to about 0.7. The reason for this paradoxical result is that the conservation incentives for the major player increase as his share of the stock increases. As stated earlier, the minor player is able to ride for free on the major player's conservation efforts.

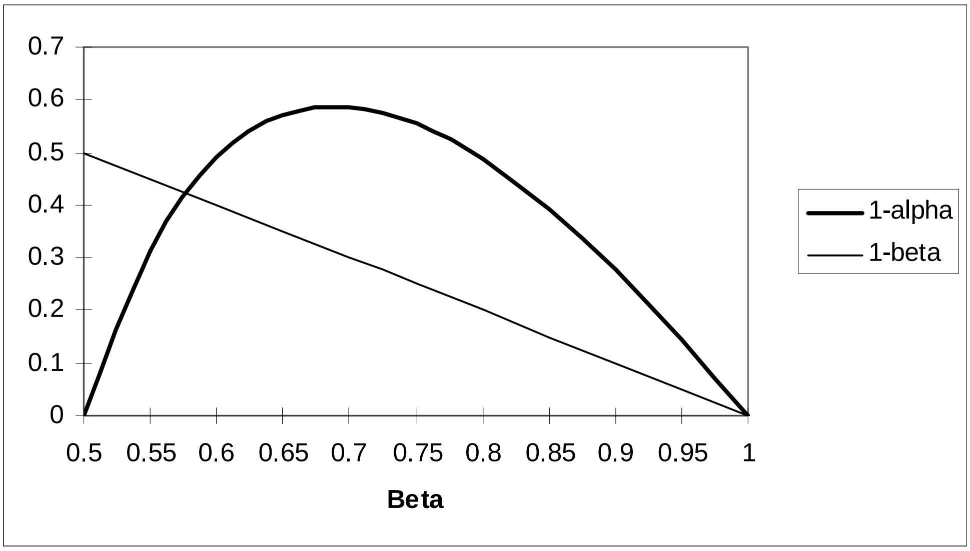

Figure 1

Common reproductive stock: Critical share in cooperative profits (1 - α) and zonal attachment of the stock (1 - β) for the minor player. Costless case.

Pure spillover

Again let us start with the globally optimal solution. Stock migrations are of no consequence for this solution; indeed the optimal solution will imply stock levels in both zones that result in no net migration, as in the pristine equilibrium. Maximizing $X_1 + X_2 - S_1 - S_2$, ignoring migrations, and using (2) to obtain the first order conditions, results in the following optimal stock levels for the two zones:

(9a) $S_1^o = \beta / 2$

(9b) $S_2^o = (1-\beta)/2$

Here the optimal stocks in the two zones are different because growth and reproduction occur in each zone and the two have different carrying capacities.

Maximizing the sustained profit for each party, taking the post-fishing stock level in the other party's zone as given, yields, using (2):

(10a) $S_1^* = \frac{\beta}{2}\left[1-\frac{\delta}{r(\beta-\delta)}\right]$

(10b) $S_2^* = \frac{(1-\beta)}{2}\left[1-\frac{\delta}{r(1-\beta-\delta)}\right]$

We see that in the non-cooperative solution the stocks in both areas are reduced relative to the cooperative solution. We see, furthermore, that the reduction is greatest in the smallest area. To obtain a positive solution for S_1 we need $r > \delta/(\beta - \delta)$ and, for S_2, $r > \delta/(1 - \beta - \delta)$. Hence, if the minor player has a too small share of the total area, he will deplete the stock in his zone to zero. For the major player, this will only happen for a "large" migration parameter δ. Compared to the case with the common reproductive stock, the risk of extinction is reduced.

Using (2) and (4b), the critical share in the cooperative solution that must be offered to the minor player is

(11)
$$(1-\alpha)\left[rS_1^o\left(1-\frac{S_1^0}{\beta}\right)+rS_2^o\left(1-\frac{S_2^0}{1-\beta}\right)\right]$$
$$\geq rS_2^*\left(1-\frac{S_2^*}{1-\beta}\right)+\delta\left[\frac{S_1^*\left(1+r\left(1-S_1^*/\beta\right)\right)}{\beta}-\frac{S_2^*\left(1+r\left(1-S_2^*/(1-\beta)\right)\right)}{1-\beta}\right]$$

which, after using (9) and (10) gives

(11') $$(1-\alpha)\geq 1-\beta+\frac{\delta^2(3\beta-2)}{r^2\beta(1-\beta)}$$

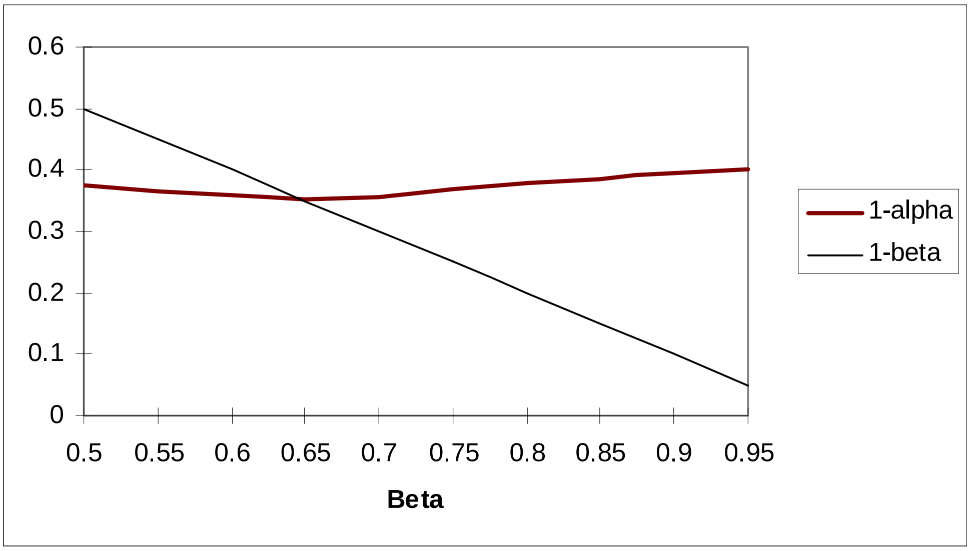

Figure 2

Pure spillover: Critical share in cooperative profits (1 - α) and zonal attachment of the stock (1 - β) for the minor player. Costless case.

Again we see that the critical share of the cooperative solution which must be given to the minor player is not equal to his share of the stock. Figure 2 compares this critical share with the share of the stock, for r = 0.5 and δ = 0.1. The critical share that must be given to the minor player is relatively constant; it in fact increases slightly as the minor player's share of the stock falls beyond a certain point. The reason is that he is able to free ride on the major party's conservation efforts, causing fish to migrate from the larger party's zone by drawing down the stock in his own zone. For the parameter used, the critical value of 1 - β at which the minor party leaves no stock behind in his zone is 0.3. At low values of 1 - β the amount of fish that the minor player sucks into his zone by depleting his own stock would be constrained by the carrying capacity of his zone. In this example this constraint is hit at β = 0.96.

Spillover with a critical threshold

The optimal stock in the cooperative solution is the same as above, one half of the total stock. Maximizing X_1 - S_1, taking the spillover into effect, gives the following first order condition (from [3a]):

(12a) $$\left[1+r\left(1-2\left(S_1+S_2\right)\right)\right](1-\delta)-1=0$$

while for the other player the first order condition (from [3b]is

(12b) $$\delta\left[1+r\left(1-2\left(S_1+S_2\right)\right)\right]-1=0$$

As in the case of a common reproductive stock, these conditions cannot be satisfied simultaneously. Provided $\delta < 0.5$, the left hand side of (12b) will be negative if (12a) is satisfied. This means that the minor player has no incentive to leave behind any of the stock, as this would mainly benefit the other party. The case $\delta > 0.5$ would imply that more than half of the emerging stock (in excess of the critical minimum) would flow over into the "minor" party's zone.

Given that the minor player leaves nothing behind after fishing, we can solve (12a) for S_1:

(13) $$S_1^* = \frac{(1+r)(1-\delta)-1}{2r(1-\delta)}$$

The major player must consider whether this stock level is more profitable than preventing the stock from spilling over into the other party's zone. If it is, we have

(14) $$r\bar{S}\left(1-\bar{S}\right) > rS_1^*\left(1-S_1^*\right)-\delta\left[S_1^*\left(1+r\left(1-S_1^*\right)\right)-\bar{S}\right]$$

Inserting (13) into (14) and turning the latter into an equality, we can find the critical combinations of the parameters δ, r and $\bar{S}$ which make it profitable for the major player to prevent the stock from spilling over into the other party's zone:

(14') $$4\bar{S}\left[r\left(1-\bar{S}\right)-\delta\right]-r(1-\delta)+2\delta-\frac{\delta^2}{r(1-\delta)}=0$$

Figure 3 shows the critical stock level ($\bar{S}$) for different combinations of δ and r. Apparently, it is not very sensitive to r but more so, unsurprisingly, to the migration rate δ.

Let us look, now, at solutions for parameter values consistent with the inequality in (14). Here, some of the stock spills over into the minor player's zone. It appears reasonable to define the "zonal attachment" of the stock to the minor player's zone as the share of the stock at the beginning of each fishing period found in his zone. Hence we get, after using (13):

$$(15) \qquad 1-\beta = \frac{\delta\left[S_1^*\left(1+r\left(1-S_1^*\right)\right)-\bar{S}\right]}{S_1^*\left(1+r\left(1-S_1^*\right)\right)} = \delta\left[1-\frac{4\bar{S}r\left(1-\delta\right)^2}{\left(1+r\right)^2\left(1-\delta\right)^2-1}\right]$$

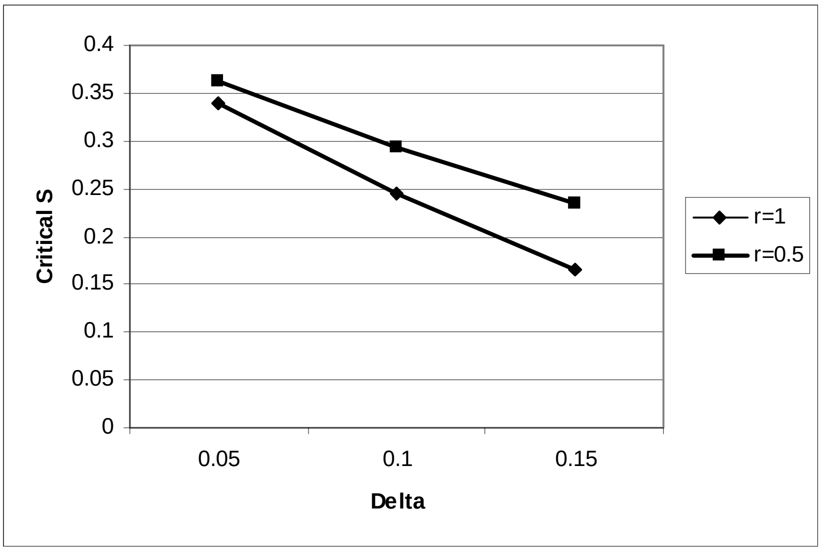

Figure 3

Stock spillover with a critical threshold: How the critical S ($\bar{S}$) depends on r and δ.

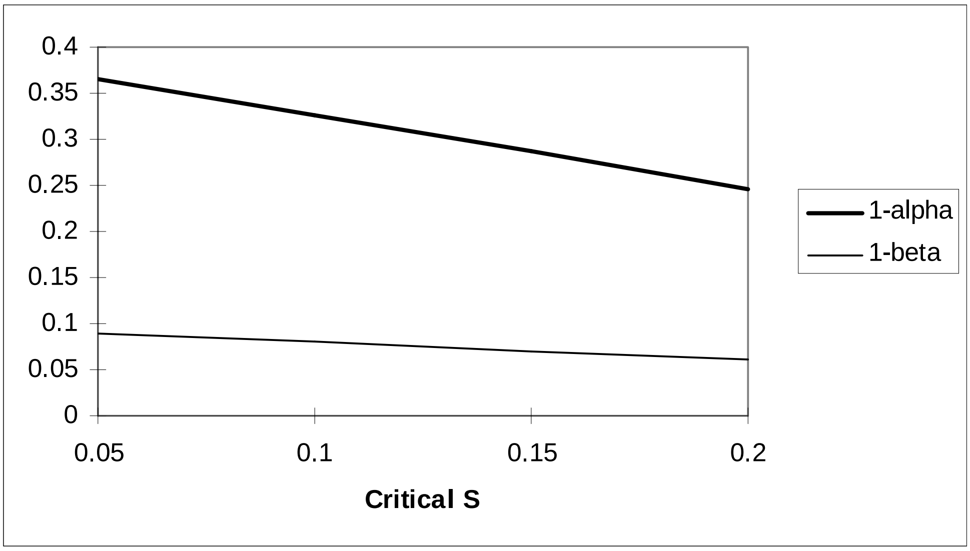

Figure 4

Stock spillover with a critical threshold: How the critical share in cooperative profits (1 - α) and the zonal attachment of the stock (1 - β) for the minor player depend on the critical S ($\bar{S}$). Costless case.

To make the cooperative solution attractive for the minor player, we need (Equation (4)):

(16) $$(1-\alpha)r/4 \geq \delta\left[S_1^*\left(1+r\left(1-S_1^*\right)\right)-\bar{S}\right]$$

or, after using (13) and (15)

(16') $$(1-\alpha) \geq \left[\frac{(1+r)^2(1-\delta)^2-1}{r^2(1-\delta)^2}\right](1-\beta)$$

For relevant parameter values the critical share (1 - α) is greater than the share of the stock (1 - β). Figure 4 compares the said shares for r = 0.5 and δ = 0.1. At $\bar{S}$ = 0.2455 his share of the cooperative solution would suddenly fall to zero, because it would be better for the major player to select this stock level and keep the fish from spilling out of his zone rather than selecting the otherwise optimal level $S_1^* = 0.389$.

STOCK-DEPENDENT UNIT COST

When the cost per unit of fish depends on the size of the exploited stock the cooperative solution is more likely to be achieved. The general reason is that both parties become more interested in fishing from a large stock in order to keep the costs down. Here we shall look at a perhaps a bit special but nevertheless very popular case where the cost per unit of fish is inversely proportional to the stock. This particular case arises from two assumptions; (i) that the cost (c) per unit of fishing effort is constant, and (ii) that the instantaneous catch (catch flow) is the product of effort and the stock times a scaling parameter. We normalize effort (E) so that the scaling parameter is equal to one, so that the instantaneous cost per unit of fish becomes $cE/ES = c/S$. With p denoting the market price of fish, the net revenue (rent) from reducing the stock from X to S over a fishing season will be

(17) $$\int_S^X (p-c/s)\,ds = p(X-S)-c(\ln X-\ln S)$$

As before, we set p = 1.

Common reproductive stock

In the cooperative solution it does not matter where the fish is caught, except that stock density must be the same in both zones, in order to minimize costs, provided the cost per unit of effort is the same in both zones. We can therefore find the cooperative solution from maximizing (17) above. Using (1), we get, from the first order condition,

(18) $$S^o = \frac{3r+2}{4r}-\sqrt{\left(\frac{3r+2}{4r}\right)^2-\frac{1+r+c}{2r}}$$

Now consider the non-cooperative solution, with each party optimizing on its own:

(19a)
$$\underset{S_1}{\text{maximize}}\ \beta(S_1+S_2)\left[1+r\left(1-(S_1+S_2)\right)\right]-S_1$$
$$-\beta c\left[\ln\left(\beta(S_1+S_2)\left[1+r\left(1-(S_1+S_2)\right)\right]\right)-\ln S_1\right]$$

(19b)
$$\underset{S_2}{\text{maximize}}\ (1-\beta)(S_1+S_2)\left[1+r\left(1-(S_1+S_2)\right)\right]-S_2$$
$$-(1-\beta)c\left[\ln\left(\beta(S_1+S_2)\left[1+r\left(1-(S_1+S_2)\right)\right]\right)-\ln S_2\right]$$

Note that the cost parameter c needs to be calibrated by the size of the two zones (β and 1 - β). A given stock in terms of total biomass S will have densities that are inversely proportional to the size of the zone over which it is (uniformly) distributed. With the catch per unit of effort being proportional to stock density (the hypothesis behind Equation (17)), the break-even stock density will be c. In (17) the stock is measured in aggregate weight, not density, so the stock levels at which the critical density will be reached are βc and $(1-\beta)c$, respectively.

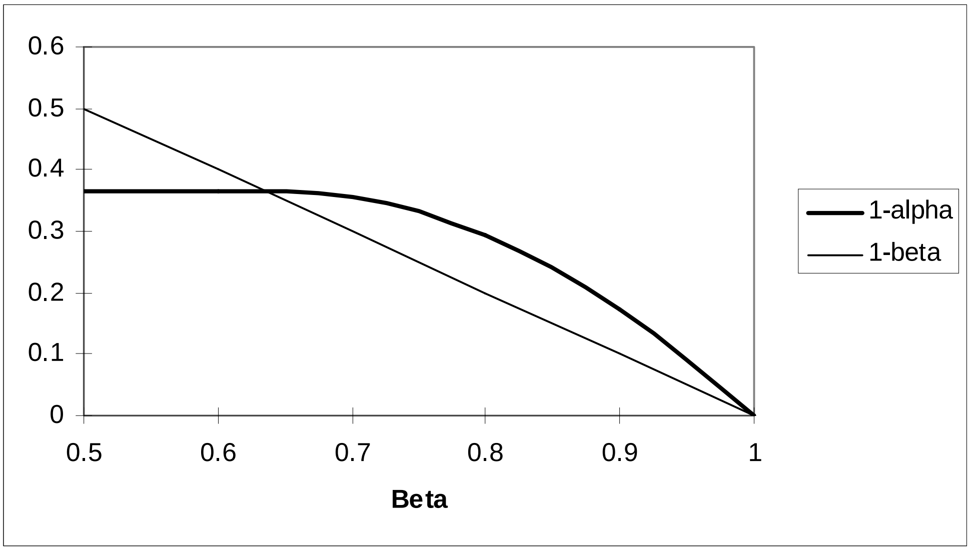

Figure 5

Common reproductive stock: Critical share in cooperative profits (1 - α) and zonal attachment of the stock (1 - β) for the minor player when unit cost depends on stock.

Using (1), we get the first order conditions

(20a)
$$\beta\left[1+r-2r\left(S_1^*+\bar{S}_2\right)\right]-1-\beta c\left[\frac{1+r-2r\left(S_1^*+\bar{S}_2\right)}{\left(S_1^*+\bar{S}_2\right)\left[1+r\left(1-\left(S_1^*+\bar{S}_2\right)\right)\right]}-\frac{1}{S_1^*}\right]=0$$

(20b) $$(1-\beta)\left[1+r-2r\left(\bar{S}_1+S_2^*\right)\right]-1-(1-\beta)c\left[\frac{1+r-2r\left(\bar{S}_1+S_2^*\right)}{\left(\bar{S}+S_2^*\right)\left[1+r\left(1-\left(\bar{S}_1+S_2^1\right)\right)\right]}-\frac{1}{S_2^*}\right]=0$$

Contrary to the case with unit cost independent of stock size, the minor player will now stop fishing before the stock has been totally depleted, as his unit cost would otherwise exceed the price. S_1^* and S_2^* can be found by numerical methods.

From Equations (4), (19) and (20) we can calculate the critical value of 1- α, the minor player's critical share in the profits in the cooperative solution. Figure 5 compares this with his share of the stock, for the same parameter values as in the costless case above and c = 0.2. As in the costless case, these two shares are not equal, but the difference is typically less than in the costless case. If the minor player has a small share of the stock he will have to be offered a larger share of the cooperative profits than corresponds to his share of the stock, again because his incentives to conserve are quickly diluted as his share of the stock falls.

Pure spillover

Here the sub-stocks grow and breed in their separate zones. Maximizing aggregate profits, we can ignore the migrations between zones as long as the cost of effort is the same in both zones; the optimal stock density will then be equal in both zones and no migration will take place. Using (2) and (17), the profit in the cooperative solution is

(21) $$\begin{aligned}\pi^o &= rS_1\left(1-\frac{S_1}{\beta}\right)-\beta c\left[\ln\left(S_1\left(1+r\left(1-\frac{S_1}{\beta}\right)\right)\right)-\ln S_1\right]\\ &+rS_2\left(1-\frac{S_1}{(1-\beta)}\right)-(1-\beta)c\left[\ln\left(S_2\left(1+r\left(1-\frac{S_2}{(1-\beta)}\right)\right)\right)-\ln S_2\right]\end{aligned}$$

From the first order conditions we find that the optimal stock levels in each zone are

(22a) $$S_1^o=\beta S^o$$

(22b) $$S_1^o=(1-\beta)S^o$$

where S^o is the optimal level of the aggregate stock, as calculated in (18).

In the non-cooperative solution, the agents maximize

(23a) $$\pi_1^*=X_1\left(S_1;\bar{S}_2\right)-S_1-\beta c\left[\ln\left(X_1\left(S_1;\bar{S}_2\right)\right)-\ln S_1\right]$$

(23b) $$\pi_2^*=X_2\left(S_2;\bar{S}_1\right)-S_2-(1-\beta)c\left[\ln\left(X_2\left(S_2;\bar{S}_1\right)\right)-\ln S_2\right]$$

Using (2), we get the following first order conditions:

(24a) $$\left[r\left(1-\frac{2S_1}{\beta}\right)\right]\left(1-\frac{\delta}{\beta}\right)-\frac{\delta}{\beta}-\beta c\left[\frac{\left(1+r\left(1-2S_1^*/\beta\right)\right)\left(1-\delta/\beta\right)}{X_1}-\frac{1}{S_1^*}\right]=0$$

(24b)

$$\left[r\left(1-\frac{2S_2}{1-\beta}\right)\right]\left(1-\frac{\delta}{1-\beta}\right)-\frac{\delta}{1-\beta}-(1-\beta)c\left[\frac{\left(1+r\left(1-2S_1^*/(1-\beta)\right)\right)\left(1-\delta/(1-\beta)\right)}{X_2}-\frac{1}{S_2^*}\right]=0$$

Again we can find S_1^* and S_2^* by numerical methods and, using (4), we get the critical share of the cooperative profits the minor player must be offered (1 - α). This is shown Figure 6, together with the minor player's share of the stock (1- β), using the same parameter values as in the costless case and c = 0.2. The result is qualitatively similar to the one for a common stock. The minor player must be offered a larger share of the cooperative profits than corresponds to his share of the stock if his EEZ is sufficiently smaller than that of the major player.

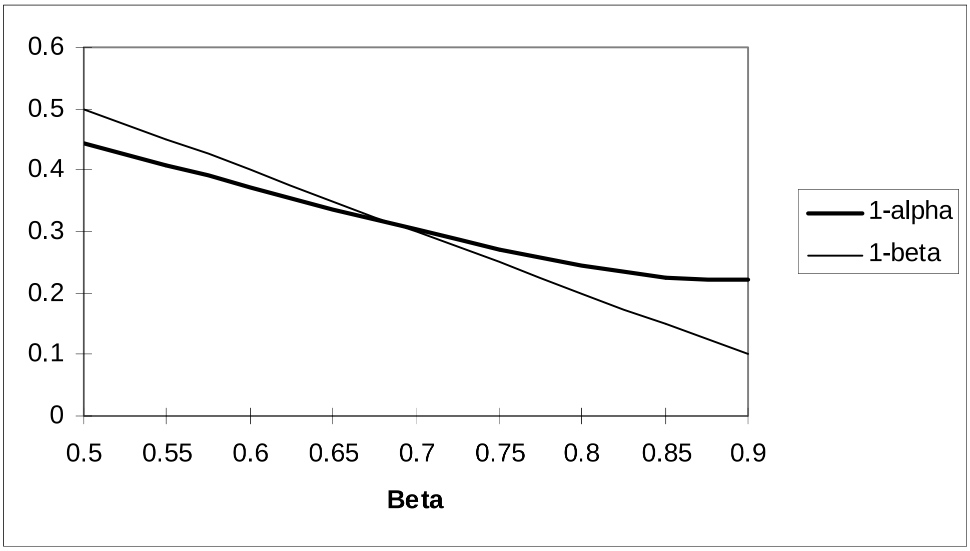

Figure 6

Pure spillover: Critical share in cooperative profits (1 - α) and zonal attachment of the stock (1 - β) for the minor player, when unit cost depends on stock.

Spillover with a critical threshold

Finally there is the case of stock migrations if the stock exceeds a critical threshold. The optimal solution is the same as in the case of a common reproductive stock (Equation [18]). The non-cooperative solution maximizes (23), as above. Using (3), we can derive the first order conditions

(25a) $$(1-\delta)\left[1+r\left(1-2\left(S_1^*+\bar{S}_2\right)\right)\right]\left(1-\frac{c_1}{X_1^*}\right)+\frac{c_1}{S_1^*}-1=0$$

(25b) $$\delta\left[1+r\left(1-2\left(S_2^*+\bar{S}_1\right)\right)\right]\left(1-\frac{c_2}{X_2^*}\right)+\frac{c_1}{S_2^*}-1=0$$

We distinguish between the cost parameters of the two agents. This does not necessarily imply different cost per unit of effort, because we now think of the cost parameters as being calibrated to take into account the difference in size between the areas in which the agents fish. Presumably the area of the spillover is much smaller, and in the example about to be discussed we set $c_1 = 0.2$ and $c_2 = 0.02$.

From (25) we can see that both agents would leave behind some fish at the end of the fishing period, as c/S approaches infinity as S approaches zero. It is not sufficient here to use (25) to find the optimal stock level; it is possible that the major agent would come out better if he leaves behind a small enough stock to make fishing by the minor agent unprofitable. This occurs if $X_2(S_1) \leq c_2$.

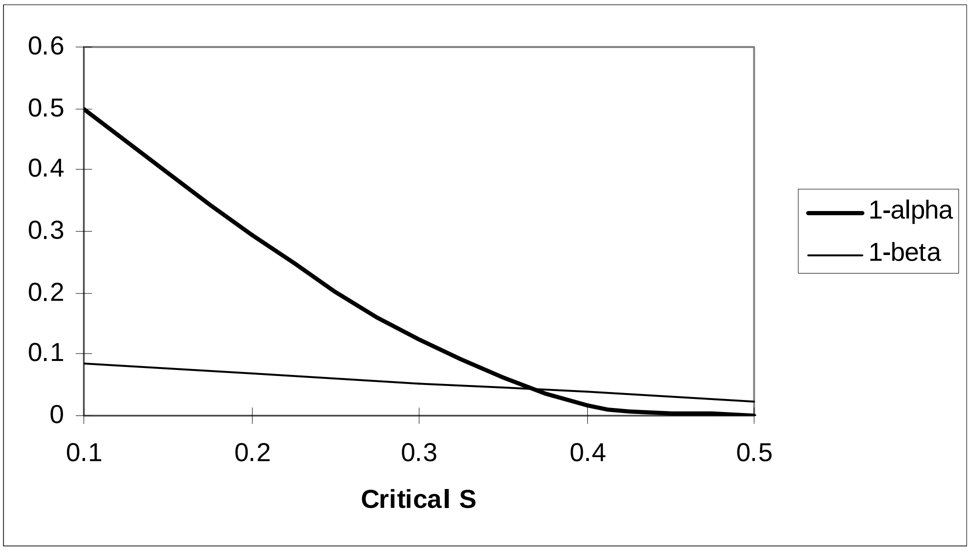

Figure 7

Stock spillover with a critical threshold: How the critical share in cooperative profits (1 - α) and the zonal attachment of the stock (1 - β) for the minor player depend on the critical S ($\bar{S}$), when unit cost depends on stock.

From (4b) we can calculate the minor agent's critical share of the cooperative solution. Figure 7 shows how this share depends on the critical stock level $\bar{S}$. As in the costless case, we have defined the minor agent's share of the stock as the share of the total stock that spills over into his area. Stock-dependent unit costs make it more costly for the major player to reduce the stock to a level that excludes the minor player, so the critical $\bar{s}$ at which the latter will become excluded is higher than in the costless case (cf. Figure 4). This result is sensitive, however, to the relative cost levels of the two players. But just as in the costless case, it is necessary to offer the minor player a much larger share of the cooperative profits than corresponds to his share of the stock, unless the critical stock level $\overline{S}$ is relatively high.

CONCLUSION

Three different migration models of a shared fish stock have been considered, one where there is a truly common reproductive stock, one where sub-stocks grow and reproduce in separate areas but spill over from one area to another, depending on relative densities, and one where a stock breeds and grows in one area but spills into another when it exceeds a certain critical size. All three models led us to conclude that fish stock sharing agreements based on zonal attachment need not be incentive compatible. It may be necessary to give a minor player a larger share in the cooperative profits, or of the total permitted catch, than corresponds to his share of the stock, in order to make him better off than he would be in the absence of cooperation. This is all the more likely to happen the smaller is the minor player's share of the stock. The smaller the player's share of the stock, the less he will gain from any conservation efforts he makes; the largest part of the benefit will accrue to the major player. Furthermore, the minor player will be able to free ride on the conservation efforts of the dominant player; the conservation incentives for the dominant player will be stronger the larger is his share of the stock. What may appear as relatively insignificant player may be able to hold out for a disproportionate and what many would be tempted to characterize as an unfairly large share of the cooperative solution. Size thus implies a certain disadvantage when it comes to sharing the spoils of cooperation. There is one exception to this, however. If stock migration across zonal borders depends on the size of the stock, the player in whose zone the stock grows and breeds might find it advantageous to keep the stock at such a low level that the fish that spill out of his zone could never be taken profitably by the other player. In that case even a small share of the cooperative solution would make the minor player better off.

Stock-dependent unit costs of fish do make some difference. While the results in this case are qualitatively similar to the ones obtained for the costless case, it is less likely that the minor player will need to be enticed with a larger share in the cooperative profits than his share of the stock. At any rate, stock-dependent unit costs reduce the necessary "overcompensation."

These results could explain why it has been difficult to reach agreement on some stocks in the Northeast Atlantic where the zonal attachment principle apparently is strong. It is perhaps surprising, given these findings, that the stock sharing agreements for the North Sea stocks have been unchallenged for twenty years or more. For these stocks the unit costs of fish are, however, probably more sensitive to the stock size than the case is for the stocks for which no agreements have been reached. This could explain why the agreements on the North Sea stocks have been so resilient.

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