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Shared stocks, game theory and the zonal attachment principle

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ABSTRACT

The outcomes of a Nash-Cournot game and a game of cooperation supported by a threat strategy are compared. The discussion is related to the ongoing conflict over the mackerel stock in the Northeast Atlantic. Despite the absence of a comprehensive management agreement, the outcome of the mackerel fishery is nowhere near what is predicted by the Nash-Cournot equilibrium. To the contrary, the countries involved seem to be engaged in an informal cooperation, supported by an implicit threat of mutually assured destruction should any single one compete too aggressively. The zonal attachment principle of dividing the total catch from shared stocks is also examined and found wanting in many cases.

1. Introduction

Many fish stocks around the world migrate across international boundaries and are, therefore, shared among two or more nations. This is the case in particular in the Northeast Atlantic. The migratory pelagic stocks (herring, mackerel, blue whiting) traverse the economic zones of four countries (Iceland, Norway, the Faeroe Islands and the pre-Brexit EU) as well as the high seas in between.

Agreements on managing these stocks have been concluded between the countries concerned, but some of these have periodically broken down, due to changes in the migrations of the stocks involved. This happened with respect to the mackerel stock after it began to appear in the Icelandic economic zone in significant quantities in 2007. The agreement was partially restored in 2014, but Iceland and Greenland are still not part of it (in recent years mackerel has been encountered in the Greenlandic economic zone).

A situation where management agreements of shared stocks break down, or the absence of such agreements, calls for a game-theoretic analysis. For non-economists, "game theory" sounds frivolous, to the point of not deserving to be taken seriously. This is unfortunate, because game theory is a serious matter indeed, dealing with the strategic interaction among firms, individuals or countries where the outcome of decisions made by one agent depends on the decisions made by other agents, implying that one particular agent had better take into account what the others might do.[1]

Problems of strategic interaction can, however, be posed in several ways, and the outcome can be critically dependent on how the problem is framed. Two such approaches will be discussed in this paper. One is the Nash-Cournot game where each player takes decisions based on hypotheses about what other players will do. Assuming full information, it makes sense to look at an outcome where the hypothetical actions of all players are the best responses to what all others do. Despite the impeccable and appealing logic of this framework it can lead to extremely destructive competition which we do not typically see being realized.

The other approach is to assume that cooperation prevails and look for how it could be supported by threat strategies. The weakness of this approach is that it does not explain how cooperation came about in the first place. The fact that gains from abandoning cooperation are transient is what basically supports cooperation once it has been established; with a low enough discount rate and a suitably severe threat strategy, gains from cooperation will outweigh gains from defection.

The mackerel fishery, for one, seems to fit the latter scenario much better than the Nash-Cournot framework, despite the rhetoric about irresponsible behavior that the parties engage in from time to time. As Fig. 1 shows, both the fish landings and the stock have been growing most of the time since the dispute began, and the fishing mortality has not increased (Fig. 2). Even if the stock growth has undoubtedly been driven by advantageous environmental conditions, an aggressive Nash-Cournot behavior would have gone a long way towards destroying the stock (Hannesson, 2013a, 2013b, 2014).

In this paper we shall use a simple model to analyze the difference between the Nash-Cournot game and threat strategies designed to uphold a preexisting cooperation. It is not our purpose to model the mackerel fishery as such; this we have done elsewhere, as already noted. We nevertheless find it interesting and motivating to have the mackerel conflict in mind and so formulate our model as a highly stylized one of the mackerel fishery. We surmise that this may indeed be a

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[1] On game theory, see for example Gibbons (1992) and Tirole (1990).

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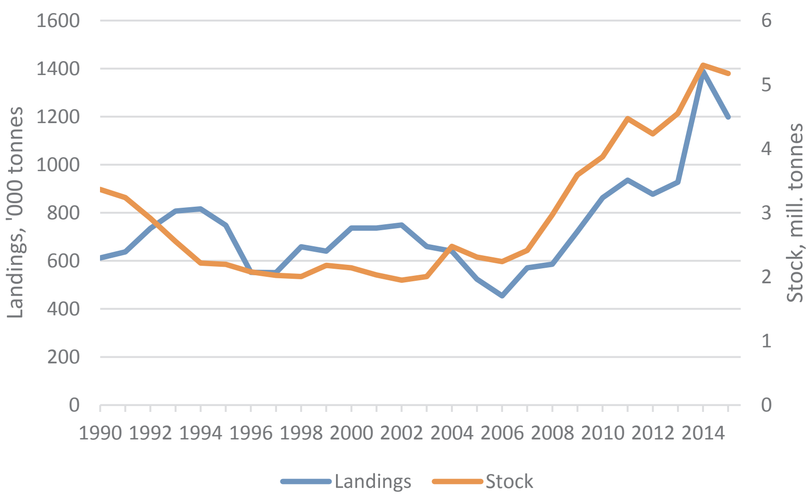

Fig. 1. Spawning stock and landings of Northeast Atlantic mackerel 1990–2015.
Source: ICES (2016).

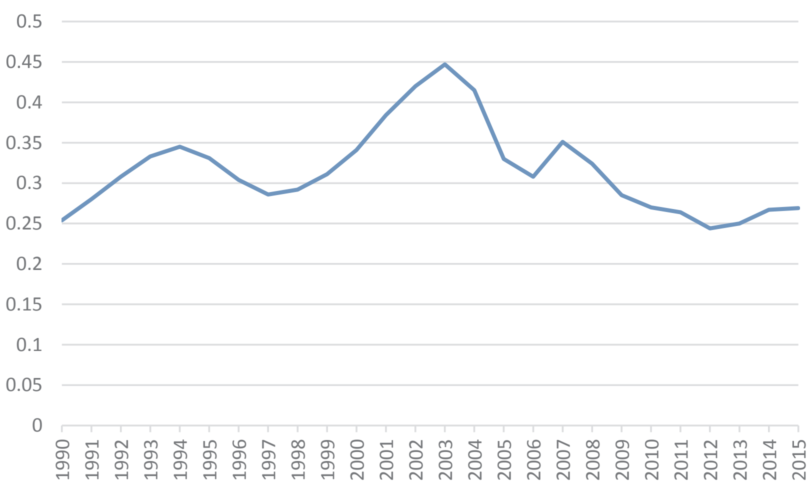

Fig. 2. Fishing mortality of Northeast Atlantic mackerel 1990–2015.
Source: ICES (2016).

suitable approach for many other migrating stocks.[2]

An additional purpose of this paper is to investigate the so-called "zonal attachment principle." It has been postulated that all that is needed to establish cooperation in management of shared stocks is to find out how much of the stock resides in each country's economic zone and distribute the total catch quota in the same way. As will be shown, this is not necessarily enough; small parties in particular may need to be brought on board with a larger share of the total catch quota than corresponds to their share of the stock.[3]

2. The Nash-Cournot equilibrium

Fig. 3 shows the geographic distribution of quarterly catches of mackerel. In the first quarter they are mainly concentrated in the spawning grounds west of the British isles. In the second quarter the stock begins to spread northwards to the economic zones of the Faeroe Islands, Norway and Iceland, and into the high seas between them. Most of the captures take place in the third quarter, and in the fourth quarter the stock is on its way back to the spawning grounds. In makes sense, therefore, to model the stock as appearing at the beginning of each fishing period in the economic zone of the individual countries and staying there until the fishing is over, whereafter it disappears and grows and breeds as one unit. Then, at the beginning of the next period, the process repeats itself. We shall not here consider variability in migrations such as have caused so much consternation in recent years; for this the reader is referred to Hannesson (2014).

A discrete time model for stock growth is

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

where X_{t+1} is the stock emerging at the beginning of period $t + 1$, S_t is the stock left after fishing in period t, and $G(S)$ is surplus growth.

For simplicity, we shall look at the fishery in a two-country setting, as this is sufficient to obtain the principal qualitative results we are interested in. One country (the major one) always gets a share $\beta \geq ½$ at the beginning of each period, with the other country (the minor one) getting the remainder $1–\beta$. The present value (V) of the major country's (Country 1) fish catches at a constant net price of fish normalized to one is

$$V = \beta X_0 - S_1 + \frac{\beta(S_1 + \bar{S}_2 + G(S_1 + \bar{S}_2)) - S_1}{r} \tag{2}$$

where r is the discount rate and S_1 is the stock left after fishing by Country 1 (the major country). For the minor country we get an analogous formulation by substituting $1–\beta$ for β. We ignore stock-dependent costs of fish, as this is not germane for the results, but makes them more dramatic.[4] We put a bar over the stock variable left behind by the minor country to indicate that it is not under control by the major country, which needs to make its best guess about what the other country will do.From (2) and the analogous problem for the minor

[2] The model is similar to one first formulated by McKelvey (see, for example, Golubtsov and McKelvey, 2007) with Pacific salmon in mind.

[3] On the zonal attachment principle, see Engesæter (1993). An earlier critique is in Hannesson (2007).

[4] For a formulation with stock-dependent unit cost of fish, see Hannesson (2007).

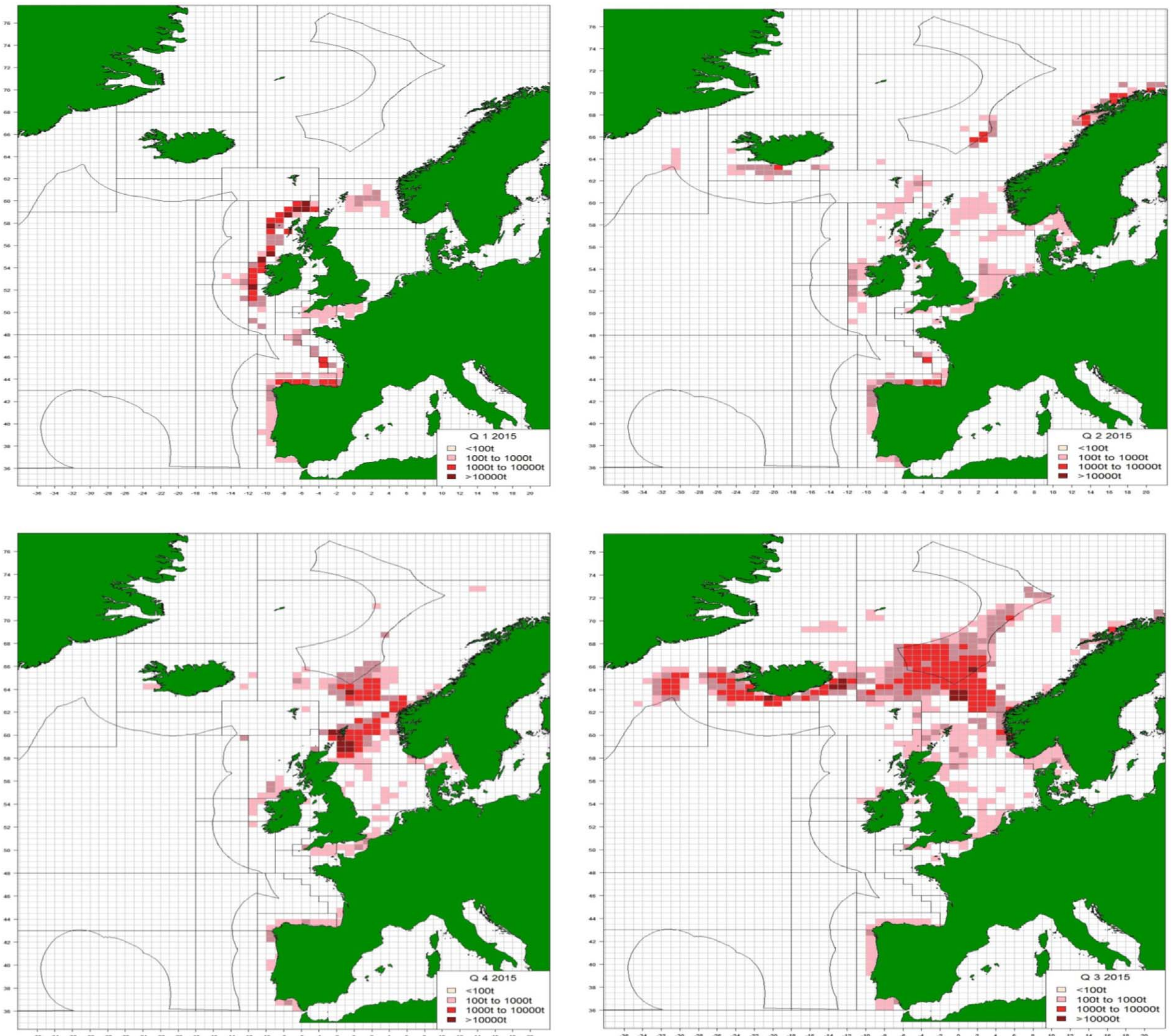

Fig. 3. Quarterly catches of Northeast Atlantic mackerel 2015, clockwise from NW-corner. Source: ICES (2016).

player we get the maximum conditions:

$$G'(S_1^* + S_2^*) \leq -1 + \frac{1+r}{\beta} \tag{3a}$$

$$G'(S_1^* + S_2^*) \leq -1 + \frac{1+r}{1-\beta} \tag{3b}$$

given that the action taken by each country is the same as the other one expects it to take ($S_i^* = \bar{S}_i$). Both of these equations cannot hold with strict equality simultaneously; the right hand side of (3b) is always greater than that of (3a) while the left hand sides of both are identical. What this means is that the minor country would always want to leave behind less fish, for whatever the major country leaves behind. But the minor country can never leave behind less than nothing, and so we end up with the minor country catching all the fish that comes its way. The intuitive explanation of this is that the minor country knows that the major country has a stronger incentive to conserve and so the minor country can ride for free on the major country's conservation efforts.

But it could also happen that the conservation incentive for the major country is so weak that it leaves nothing behind as well. This, in fact, is by no means unlikely. Rewrite (3a) to get (note that the major country is the only one that leaves anything behind)

$$\beta(1 + G'(S_1^*)) \leq 1 + r \tag{3a'}$$

What we have on the left hand side is the return to the major country from leaving one unit of fish behind. This will have grown to $1 + G'$ next period, but the major country gets only a share β of this. Catching the fish and investing the money "in the bank" will have grown to $1 + r$ at the beginning of the next period. This requires a rather high rate of growth of fish stocks if they are to be viable in this setting.[5] For a viable stock, we need a reverse inequality at $S = 0$, implying

$$1 + G'(0) > \frac{1+r}{\beta} \tag{4}$$

With $\beta = ½$ and $r = 0$, we would need $G'(0) > 1$, that is, a maximum growth rate of more than 100 percent, which is likely to be beyond the capacity of most fish stocks. In a multi-player setting where the dominant player could have a stock share (β) well below ½ the maximum growth rate would have to even higher. In the mackerel case, EU (pre-Brexit) is the dominant player, with a share of about 40 percent in recent years (see Fig. 4).

We conclude that a Nash-Cournot type of game is highly likely to result in a total annihilation of a fish stock shared between two or more countries, unless the cost per unit of fish depends on the stock, making

[5] Extinction of fish stocks as a result of a high discount rate was first discussed by Clark (1973, 1976).

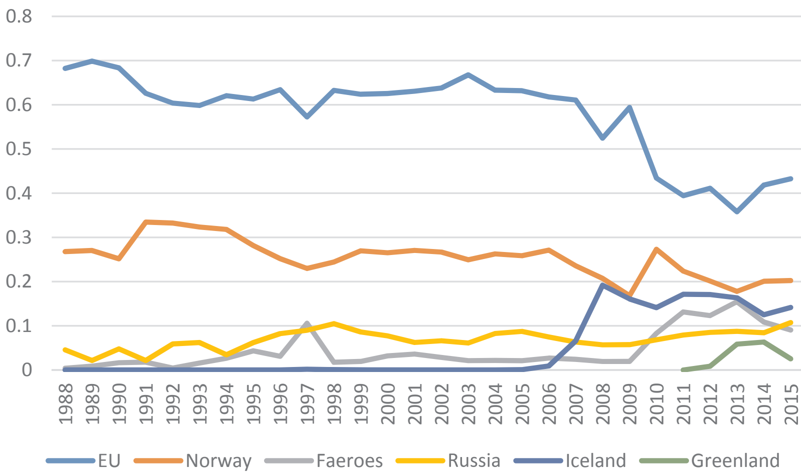

Fig. 4. Shares of catches of Northeast Atlantic mackerel 1988–2015. "EU" comprises all member countries as of 2016, even those that joined after 1988. Compiled from ICES (2016).

further decimation unprofitable at some critical stock level. The mackerel setting is quite likely to be of the former type. The countries sharing the stock do not seem at all concerned about how costs per unit of fish might rise with a dwindling stock; what they seem concerned about is sustainability of the fishery, the total catch quota and its distribution among the participating countries. The fishing technology (purse seining) is also of a type that probably makes the cost per tonne of fish insensitive to the size of the stock. This setting fits the model we have been using, but as already indicated, the outcome of the fishery in recent years is nowhere near the annihilation we would expect on the basis of the Nash-Cournot approach.

Before finishing with the Nash-Cournot approach, let us consider how the zonal attachment principle would fare in this setting. To make the cooperative solution attractive to the minor player, he would have to be offered an outcome at least as good as what he would get in the absence of cooperation. If his share of the cooperative fish quota is 1–α, his participation constraint would be

$$(1-\alpha)G(S^o) \geq (1-\beta)(S_1^* + G(S_1^*)) \tag{5}$$

where S^o is the globally optimal stock and S_1^* is the stock left by the major country after fishing in the Nash-Cournot solution. For illustration, we shall use the logistic growth function

$$G(S) = aS(1-S) \tag{6}$$

where a is the maximum relative growth rate and the carrying capacity is normalized at 1. We set $a = 0.5$, which is in fact quite high and higher than the maximum growth rate is likely to be for the mackerel.[6] With $r = 0.05$, viability of the stock requires in this case $\beta \geq 0.7$ [see (4)]. We see from Fig. 5 that for $\beta \geq 0.75$ the minor player needs to be offered a share of the cooperative quota in excess of what his zonal attachment would dictate. The reason is that as the major player's share of the stock increases, his incentive to conserve becomes stronger, and he leaves behind a larger and larger stock, which increases the free-riding gains of the minor player.

3. Cooperation supported by a threat strategy

Now let us consider the alternative setting where cooperation has been established and is supported by a threat strategy that makes non-cooperation unattractive for a single player.[7] If the minor player decides to stop cooperating, he would presumably make the most of the gains he could get and leave no fish after fishing (the Nash-Cournot strategy). The major player would, in turn, choose the best possible reply to this move, again the Nash-Cournot strategy (S_1^*). Suppose the minor player stops cooperating in Period 0, but is found out at the end of that period. Then, from Period 1 on, both players will play the Nash-Cournot strategy. The condition that non-cooperation be unprofitable is

$$\frac{(1-\alpha)G(S^o)(1+r)}{r} > (1-\beta)[S^o + G(S^o)] + \frac{(1-\beta)[S_1^* + G(S_1^*)]}{r} \tag{7}$$

Three questions can be asked at this point. First, could cooperation be supported by following the zonal attachment principle ($1 - \alpha = 1 - \beta$), for a given discount rate? Second, could some reasonable discount rate make the zonal attachment principle sufficient to entice cooperation? Third, for how long would the Nash-Cournot punishment strategy have to be followed to make defection from cooperation unprofitable? This is of interest because the minor player could always mend his ways and promise to return to cooperation. Refusing to do so might not be in the major player's best interest, but in order to make the threat strategy effective, non-cooperation would have to be followed for some time. It may be noted that this last question is only relevant if the Nash-Cournot strategy results in a viable stock (that is, if the major player leaves some fish behind after fishing).

We use again the logistic model [Eq. (6)] with $a = 0.5$. We begin with the zonal attachment principle and ask if, for a given r, the inequality in (7) will hold for $1 - \alpha = 1 - \beta$. The answer is, probably not. Fig. 6 illustrates two cases (with $r = 0.05$ and $r = 0.1$). The figure shows the minimum share of the cooperative catch quota ($1 - \alpha$) that needs to be offered to the minor player to entice him to cooperate. We see that if the major player's share of the stock exceeds a certain level, the minor player must be offered a larger share of the cooperative catch than corresponds to his share of the stock. The result is very similar to the one we obtained when directly comparing the sustained payoffs to cooperation versus Nash-Cournot equilibrium (Fig. 5), and the intuitive explanation is the same; more gains from free riding by the minor player as the major player's share of the stock and his incentive to conserve increase. The kink in the curve is due to the fact that for lower values of β the major player will fish out the stock in a Nash-Cournot equilibrium.

From Fig. 6 we see that the zonal attachment principle works for more values of β the lower the discount rate is. Consider then the question whether some reasonable discount rate would make the zonal attachment principle sufficient to achieve cooperation. Cancelling the factors $1 - \alpha = 1 - \beta$, we seek the critical r^* that turns (7) into an equality. Using the logistic function [Eq. (6)], we get a quadratic equation for r^* with the solution

[6] In Hannesson (2013a), the maximum growth rate of the mackerel stock, using the logistic model, was estimated at just below 0.4.

[7] An early consideration of threat strategies in renewable resource games is Kaitala and Pohjola (1988).

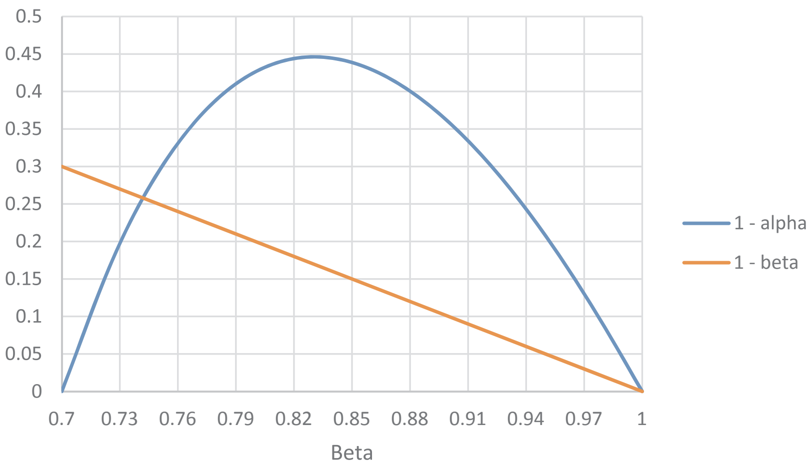

Fig. 5. The minor player's critical share (1 − α) of the cooperative fish quota compared with the zonal attachment (1 − β).

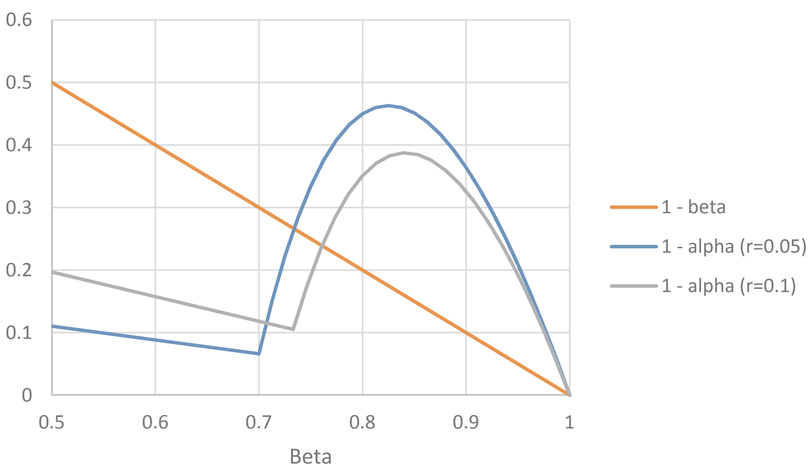

Fig. 6. The minor player's critical share (1 − α) of the cooperative catch quota needed to support cooperation compared with the zonal attachment (1 − β).

$$r^* = -\frac{1}{2}A \pm \sqrt{\frac{1}{4}A^2 - B} \tag{8a}$$

$$A = \frac{2(1 - a\beta^2)}{1 + \beta^2} \tag{8b}$$

$$B = \frac{1 - \beta^2 - 2a\beta^2}{1 + \beta^2} \tag{8c}$$

Fig. 7 shows how the critical discount rate depends on the major player's share of the stock (for $a = 0.5$), the higher β is, the higher is the discount rate that would deter the minor player from refusing to cooperate on the basis of the zonal attachment principle. Note the somewhat paradoxical result that, for a given β, a high discount rate is needed to deter the minor player from not cooperating. The reason is that a lower discount rate would increase the optimal stock to be left behind by the major player, which would increase the minor player's gains from not cooperating. As β increases, a higher and higher discount rate is needed to deter the minor player from not cooperating. For most of the relevant β-values in this example the critical discount rate is unreasonably high; as β increases beyond 0.8 it rises above 17 percent.

Finally, consider the question of for how long the punishment of a minor player who abandons cooperation would have to go on to be

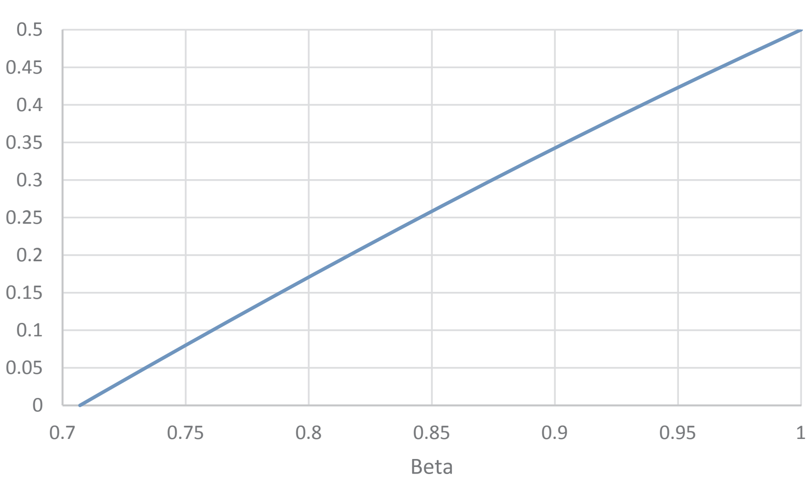

Fig. 7. How the critical discount rate for making the zonal attachment principle work depends on the major player's share of the stock (β), for a maximum rate of growth of 50 percent.

Table 1
How the minimum punishment period (*T*) necessary to support a cooperative solution changes as the minor player's share of the cooperative solution (1–α) is increased above minimum (same model as in Fig. 6).

1–α	*T*
0.46299	Infinity
0.47	24.6
0.48	13.5
0.5	6.9

credible. With the last punishment period denoted by *T*, (7) becomes

$$\frac{(1-\alpha)G(S^o)[1+r-(1+r)^{-T}]}{r} > (1-\beta)[S^o + G(S^o)] + \frac{(1-\beta)[S_1^* + G(S_1^*)](1-(1+r)^{-T})}{r} \qquad (7')$$

Or, solving for *T*:

$$T \leq -\frac{\ln\left[\frac{r(1-\beta)[S^o+G(S^o)]+(1-\beta)[G(S^*)+S^*]-(1-\alpha)(1+r)G(S^o)}{(1-\beta)[S^*+G(S^*)]-(1-\alpha)G(S^o)}\right]}{\ln(1+r)} \qquad (9)$$

If the minor player gets the minimum share which will entice him to accept the cooperative solution, (7) will hold with equality, which implies that the numerator in the expression ln(.) is equal to zero, and an effective punishment will have to go on forever; the necessary punishment strategy can be grim indeed. But *T* is sensitive to changes in the minor player's share of the cooperative solution. If $(1-\alpha)$ is set higher than the minimum necessary to entice him to cooperate (Eq. (7) holds with inequality), a finite punishment period will be enough. Consider the example shown in Fig. 6 (with $r = 0.05$), in particular the solution for $\beta = 0.825$, giving $1-\alpha = 0.46299$. Table 1 shows how the necessary punishment period becomes shorter as the minor player's share of the cooperative solution increases to 0.5. It could thus be argued that a greater generosity by the major player in accommodating the minor player would pay off in not having to apply the harsh punishment for as long in case the minor player deviates from cooperation.

4. Conclusion

Countries sharing a migrating fish stock are engaged in a strategic game; the outcome of what one does depends on what others do. They are, furthermore, sufficiently few for the actions of one to have a significant effect on the others. There is more than one way of setting up such strategic games, however. Some, in particular the Nash-Cournot approach, can lead to extremely destructive outcomes.

Despite the breakdown of a formal agreement, the outcome of the mackerel fishery in the Northeast Atlantic comes nowhere near to accord with the predictions of the Nash-Cournot game. The countries involved seem to know better than being interested in depleting the fish stock on which they all depend through unfettered competition. Instead they seem to be engaged in an informal cooperation which is perhaps not far from what they would do with formal cooperation. It is as if cooperation is being maintained by an implicit threat of mutually assured destruction, a bit like what kept the peace in the cold war, in case any one of them were to deviate radically and approach the Nash-Cournot outcome. This seemingly implicit cooperation is likely to be facilitated by the fact that the countries involved also share other pelagic fish stocks (Norwegian spring-spawning herring, blue whiting) and cooperate in setting quotas for these. Like the mackerel agreement, the one on the Norwegian spring-spawning herring broke down in 1995 for a similar reason (expected changes in migration did not materialize), but was resumed after two years. In the meantime the countries involved had set unilateral quotas in order to establish "catch history". These unilateral quotas nevertheless seem to have been moderate; the stock was nowhere near being threatened by them.[8]

A more realistic, and certainly more optimistic, way of formulating the strategic situation is to look at how cooperation can be maintained through implicit or explicit threat strategies. Effective threat strategies may, however, be very grim indeed, similar or identical to the Nash-Cournot equilibrium, and they may have to be played for a very long time and possibly indefinitely to be effective.

A referee has raised the question how fluctuations in fish stocks might affect the results, pointing to a paper by Rotemberg and Saloner (1986) which showed that oligopolistic behavior is more likely to break down in periods of high demand, due to higher payoff to defection from cooperation. In the fisheries case the analogy would be a greater risk of breakdown in periods of resource abundance. This is a problem worthy of investigation in its own right and has not been attempted here. Suffice it to say that the breakdown of the mackerel agreement and subsequent implicit cooperation occurred in a period of high abundance.

We have also looked at the adequacy of the zonal attachment principle for sharing the cooperative catch quota. This principle sounds intuitively plausible; countries should get the same share of the total catch quota as they have of the stock. Unfortunately, this is not sufficient to entice small players to accept a cooperative solution rather than act as free riders on the conservation efforts of more substantial players. Small players would typically have to be offered a larger share of the total catch quota than corresponds to their share of the stock. This could be considered unfair, and particularly so in situations where the minor player ends up taking a substantially larger catch than the player with a larger share of the stock, a situation that can easily happen if the major player does not have much more than one half of the stock.

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[8] On this and cooperation on pelagic species in the northeast Atlantic, see Bjørndal (2009).