SNF Working Paper No. 08/07

Cooperative Equilibria in Fisheries: How Many Players?

Rögnvaldur Hannesson

SNF project No. 5255: "Strategic Program in Resource Management"
The project is funded by The Research Council of Norway

INSTITUTE FOR RESEARCH IN ECONOMICS AND BUSINESS ADMINISTRATION
BERGEN, APRIL 2007
ISSN 1503-2140

Abstract

This paper investigates conditions under which fisheries agreements between states are self-enforcing. Cooperative solutions can be self-enforcing if parties to the agreement punish those who depart from the cooperative solution by doing likewise, thereby causing a loss to the deviant that outweighs transient gains from deviation. Two kinds of deviation are examined: (i) effort deviation and (ii) time deviation. Both of these are linked to the excess capacity available in the fishery. It is investigated how the number of players that can be accommodated in a cooperative solution depends on fishing costs, the discount rate, and the growth rate of the fish stock, for a given level of excess fishing capacity. Furthermore, it is investigated how the possibility of maintaining a cooperative solution depends on the level of excess fishing capacity, and whether or not it would be profitable to invest in excess fishing capacity. Finally it is discussed how cost differences among players will affect the viability of the cooperative solution.

Revised April 2007

1. **INTRODUCTION**

For a number of reasons, fish stocks are difficult to manage. One reason is fluctuations in stock growth, caused by variability of the environment beyond human control. Another is migration of fish across national boundaries. Management of fish stocks that migrate between the economic zones of two or more countries requires cooperation among the countries involved. Such cooperation is likely to become increasingly difficult the more countries that are involved. It will be particularly difficult on the high seas where no single country has jurisdiction, because the number of parties with a potential interest is not only large but indeterminate.[1]

This paper investigates how the viability of cooperative fisheries agreements depends on the number of participants involved. Since such agreements are concluded, or implicit, among sovereign states they must be self-enforcing, i.e., each party must find it in its interest to adhere to such agreements without any coercion from the outside. The approach taken here is based on one of the so-called Folk Theorems in game theory.[2] A deviation by a single player from the cooperative solution will only provide short term gains, as the remaining players will, in their own interest, retaliate by also departing from the cooperative solution. Provided the discount rate is low enough, no single participant has an incentive to deviate from the cooperative solution maximizing the aggregate return. But, as will be shown, the losses from deviating from the cooperative solution will be smaller the more participants there are.

This paper follows up an earlier paper (Hannesson, 1997) which looked at deviations where one player reduces the fish stock from the optimal level (the cooperative equilibrium) to the break-even level over one period, followed by the remaining players doing likewise in subsequent periods. This stock depletion by the deviant player gives him a once and for all gain in the form of a temporarily large catch of fish. The question what this means in terms of excess fishing capacity or time available for the extra stock depletion was left open, however. This is the subject of the present paper.

Whatever form cooperative management of fish stocks takes, it involves a formal or an informal agreement to apply only a limited amount of fishing effort, consistent with the amount of fish it is desired to leave behind after fishing.[3] Fishing effort has two major dimensions, a capacity dimension and a time dimension. Fishing capacity is related to the number and technical specification of fishing boats, and the fishing effort they produce is the product of their capacity and the time they are used. Keeping the effort within agreed limits thus involves applying only a limited number of boats for a limited amount of time. Deviations from the cooperative solution could thus take either of two forms and possibly both; (i) more boats are used than agreed, or (ii) the boats being used fish longer than agreed. The latter presupposes that it is technically possible to extend the fishing season, which would imply that there is some excess capacity that is reigned in by not using it for as long a period

[1] The obstacles to cooperation have been investigated in a number of papers. See, e.g., Lindroos and Kaitala (2000), Brasao, Duarte and Cunha-e-Sa (2000), Arnason, Magnusson and Agnarsson (2000), and Pintassilgo (2003).
[2] See, e.g., Rasmussen (2001).
[3] In continuous time models without external fluctuations, cooperative fishing would involve continuous fishing at an even rate from a steady-state optimal stock. The model used in this paper is a discrete time model where fishing occurs over a certain period, leaving the stock to replenish until the beginning of the next fishing period. This kind of model is more in tune with reality where there are seasonal fluctuations in nature, generating seasonality in the fishery.

as possible. In any case, deviation from the cooperative solution is possible only if there is some excess capacity to produce effort beyond what is needed in the cooperative solution.

It is convenient to refer to these two kinds of deviations as (i) the effort deviation and (ii) the time deviation, although this is imprecise; the time deviation necessarily implies greater effort exerted by the deviating party; the only difference is that this comes after the other parties have stopped fishing. If a time deviation is to be possible, it must be true that the fishing could go on longer than it in fact does, whether the fishing time is limited by natural conditions having to do with the accessibility of fish or by the calendar year, in case the fish are equally accessible at all times. It is most relevant, therefore, to think of the time deviation occurring in a situation of overcapacity where the fishing season has been shortened because there is more than enough latent effort to catch the permitted quota of fish.

Reducing the stock from the optimal to the break-even level typically requires very substantial excess capacity. In the time deviation case the fishing would have to be concentrated to a very short interval in the fishing season (or the calendar year) in order to give a deviant player the opportunity to fish the stock down to the break even-level and ensure maximum return from deviation. To some extent this is the consequence of the production function assumed (the Schaefer function), but would be present in milder form if the catch per unit of effort is less dependent on the size of the exploited stock. In any case, once we make a realistic assumption about available excess capacity (say, fishing for a quarter to one half of the fishing season instead of a small fraction like one tenth or less, or a threefold overcapacity instead of tenfold or more), it becomes possible to accommodate many more players in the cooperative equilibrium than if there are no constraints on time or capacity. Furthermore, this would not require a long punishment period.

Excess capacity may not be available, but it can be built. We next look at the gains from deviation per unit of new capacity and compare this to the incentive the other players have to respond to the capacity expansion by doing likewise and retaliate by fishing down the stock. As the number of participants increases, the gain per unit of new capacity increases relative to what the other players gain by retaliating. The critical number of players is the one where these two balance. Taking these capacity costs into account raises the number of players compatible with a cooperative solution, the more so the higher the costs of fishing. In some cases the number could be about twice what it is in the case of freely available excess capacity.

The final question considered is cost differentials. What happens if all players do not have the same cost of fishing? This is analyzed in a model where one player has lower fishing costs than the other players. This obviously increases the advantage the low cost player has from deviation. It is found that the critical number of players compatible with a cooperative solution falls dramatically with only minor cost differentials.

2. THE MODEL

The growth of the stock is modeled as follows:

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

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

According to this formulation, fishing and stock growth are separated in time, with fishing occurring first and growth and death taking place afterwards. Needless to say, this is a simplification. It could, however, be reasonably realistic when fishing is seasonal and concentrated to a relatively short period.

We shall use the Schaefer production function. This implies that the rate of change in the fish stock due to fishing is proportional to the product of fishing effort and the size of the fish stock. Fishing effort has a capacity and a time dimension; effort is the product of capacity utilized (K) and the time spent fishing (T): [4]

(2) $$E = KT$$

Hence, increase in fishing effort is the result of an increase in capacity utilized or the time spent fishing, or both. Effort could also increase even if less time is spent fishing, provided the increase in capacity utilized outweighs the contraction of the time spent fishing.

The stock left after fishing is

(3) $$S_t = X_t e^{-E}$$

From this we get

(4) $$E = \ln X_t - \ln S_t$$

The amount of fish caught in period t is X_t - S_t when we ignore growth during the fishing period. Let c denote the variable cost of effort. With a given price (p) of fish, the profit is[5]

(5) $$\pi = p\left(X_t - S_t\right) - c\left[\ln X_t - \ln S_t\right]$$

3. DEVIATION WITH NO LIMITS TO CAPACITY

The cooperative solution to the fisheries management problem will be defined here as leaving behind after fishing a stock (S) that maximizes the present value of profits. For a given initial stock $X_0 > S^o + G(S^o)$, where S^o is the optimal steady-state stock to be left after fishing, the present value of the fishery profits is:

(6) $$V^o = p\left(X_0 - S^o\right) - c\left[\ln X_0 - \ln S^o\right] + \frac{1}{r}\left\{pG\left(S^o\right) - c\left[\ln\left(S + G(S^o)\right) - \ln S^o\right]\right\}$$

[4] Capacity is the number of standardized boats in the fishery. Measuring capacity is not trivial, since boats differ, and the capacity of each boat depends on fishing gear and other outfit and technical parameters. This definition of capacity differs from what is standard in production theory, where capacity is defined in terms of the goods produced. Here capacity produces fishing effort which interacts with the stock of fish to produce fish catches.

[5] This notion of profit is revenue in excess of variable costs and thus includes the contribution to covering fixed and quasi-fixed costs. Quasi-fixed costs are costs necessary to engage in fishing in any given period but independent of the length of the fishing period. An example is insurance fees that do not depend on the length of the fishing period and can only be avoided by laying up the vessel. Even costs of going to the fishing areas and back would be quasi-fixed, as they are presumably independent of the size of the stock. The stock-dependent costs are therefore likely to be a rather small fraction of total costs. For an empirical investigation, see Hannesson (forthcoming).

To apply the Folk Theorem, we need to consider what constitutes a deviation from a cooperative solution. We shall assume that the deviating party reduces the stock to its break-even level, either by applying more effort during the fishing period (effort deviation), or continuing to fish after the others have stopped (time deviation). In the period of deviation the other participants continue apply the cooperative level of effort, but find out after that period is over what has taken place, or are unable to respond earlier. In the next and all subsequent periods the other players also participate in depleting the stock to the break-even level, as this is their best response to the deviant's behavior.

We also make the assumption that all parties are of equal size. All of these are simplifying and somewhat questionable assumptions. What has happened may become obvious to the other parties long before the period of deviation is over. The parties would then, presumably, take punitive action already during the period of deviation, which would make deviation less profitable than otherwise. Investigating how the outcome of the game is impacted by the time lag to discovery is a worthwhile subject, but will not be dealt with here. The assumption that the offended parties will respond by deviating from the cooperative solution for ever is also problematic, in the sense that a shorter punishment phase could be sufficient to deter any party from deviating. The parties could agree to resume the cooperative solution at a later date, but the punishment phase would have to go on for some time in order to work, a point which we will return to below. Finally, the assumption that all parties are of equal size is artificial and also worthy of further investigation.

If deviation is not profitable, the following must hold:

(7) $$\frac{\pi^o(1+r)}{r} > \pi^d + \frac{\pi^*}{r}$$

where π^o is the annual sustained profit in the optimal solution. The term π^* is the annual sustained profit in the punishment phase, here assumed infinite, while π^d is the profit during the period of deviation.

The deviation will initially be assumed to be the most severe possible, each participant having sufficient fishing capacity to reduce the fish stock to its break-even level *c/p*. That this is the break-even level can be seen as follows. The flow of cost per unit of effort is *cE* while the flow of catch is *Ex*, where *x* is the level of the stock being fished at a given time point during the fishing period. The cost flow per unit of fish caught is therefore *c*/*x*, and the profit realized during the fishing period is

(8) $$\pi = \int_{S_t}^{X_t}\left(p - \frac{c}{x}\right)dx = p(X_t - S_t) - c\left[\ln X_t - \ln S_t\right]$$

which is the same as (5) but derived in a different way. As is clear from the integral term, the flow of profits will become zero when the stock has reached the level $x = c/p$.

The deviant's profit during the period of deviation depends on whether it is a time deviation or an effort deviation. In the time deviation case, the deviant player continues fishing after the other players have stopped. His profit will then be as follows:

$$(9) \qquad \pi_T^d = \frac{1}{N}\left\{pG\left(S^o\right) - c\left[\ln\left(G(S^o) + S^o\right) - \ln S^o\right]\right\} + p\left(S^o - c/p\right) - c\left(\ln S^o - \ln\left(c/p\right)\right)$$

In the period of deviation, the deviant player gets his $1/N$-th share of the cooperative solution while all players are fishing down the stock to the optimal level. After that he continues fishing until the stock has been reduced to the break-even point and no further profits can be realized.

In the next period the other players have discovered the deviation and retaliate by participating in fishing down the stock to the break-even point. From that period on the deviant player's (and the other players') profit will be

$$(10) \qquad \pi^* = \frac{1}{N}\left\{pG\left(c/p\right) - c\left[\ln\left(G(c/p) + c/p\right) - \ln\left(c/p\right)\right]\right\}$$

In the effort deviation case, the deviant player's profit during the period of deviation will be determined by his share of total effort. The deviant player will be able to increase his share of the total profit during this period by a unilateral increase in effort. The deviant player's profit in the period of deviation is

$$(11) \qquad \pi_E^d = \frac{E^d}{E^d + E^{-d}}\left\{p\left(S^o + G\left(S^o\right) - c/p\right) - c\left[\ln\left(S^o + G\left(S^o\right)\right) - \ln\left(c/p\right)\right]\right\}$$

where E^d is the deviant player's effort during the period, and E^{-d} is the effort applied by all the others and which is equal to the effort they apply in the cooperative solution. Note that it will not be profitable to continue fishing beyond the time when the stock has reached the break-even level, as the flow of profits would be negative. Hence, in order to maximize the payoff from deviation, the deviating agent will increase his effort as much as possible. Noting that effort is the product of capacity and fishing time, we have

$$(12) \qquad \frac{E^d}{E^d + E^{-d}} = \frac{K^d T}{\left(K^d + K^{-d}\right)T} = \frac{K^d}{K^d + K^{-d}}$$

and the deviating agent will increase his share of the profit in the period of deviation by using all his capacity available, or build new to the extent profitable, as will be discussed below. Note that the greater capacity used by the deviating agent will shorten the fishing time T, but T cancels out of the share expression as it affects all agents in the same way.

From the next period on, every player will have an incentive to apply all his effort fully from the beginning of the fishery, to ensure he gets the maximum possible share of the profits. If, for simplicity, we assume that all players have the same fishing capacity, each will get the same share of the profit flow from the second period on, exactly as in the time deviation problem.

Parallel to the time deviation above, we will make the assumption that the deviant player has sufficient capacity to reduce the stock to the break-even level. Contrary to the time deviation, the deviating agent may use more capacity than strictly necessary for this. The reason is that the deviating agent will increase his share of the catches by doing so. As the deviating agent increases his effort beyond a certain level the time fishing will shrink, because no one will continue fishing beyond the time the flow of rents turns negative. The attractiveness of deviation will thus increase the greater excess capacity the deviating agent has. Here we shall assume that the deviating agent has just sufficient capacity to reduce the stock to the break-even level without affecting the time fishing, and that the other agents have the same excess capacity to retaliate in the periods thereafter. The fishing time will therefore shrink in these later periods.

It is unclear which kind of deviation will be most profitable, for any given number of players. The share (s) the deviant player takes of the catch during the period of deviation is

$$s = \frac{E^d}{E^d + E^{-d}} > \frac{1}{N} \tag{13}$$

The difference in profits during the period of deviation can be written

$$\begin{aligned} \pi_T^d - \pi_E^d = & \left[pG\left(S^o\right) - c\left(\ln\left(G\left(S^o\right) + S^o\right) - \ln S^o\right)\right]\left(\frac{1}{N} - s\right) \\ & + \left[p\left(S^o - c/p\right) - c\left(\ln S^o - \ln\left(c/p\right)\right)\right]\left(1 - s\right) \end{aligned} \tag{14}$$

which has an ambiguous sign, because of (13) and $s < 1$.

We can now use (7) above to find the number of players consistent with a cooperative solution. With the assumptions that have been made, the difference lies in the term π^d, while π^* and π^o are identical under both deviations. To illustrate, we shall use the discrete-time logistic function

$$G(S) = aS\left(1 - S\right) \tag{15}$$

where the carrying capacity has been normalized at 1. The growth parameter a is the maximum relative rate of growth ($G(S)/S$).

The time and effort deviations are compared in Figure 1, for various combinations of parameters. It clearly makes a difference what form the deviation takes, i.e., whether it is a time deviation or an effort deviation. Also it would make a difference in the effort deviation case how much excess effort the deviant agent has available; here it has been set equal to what is sufficient to drive the stock down to the break-even point.

Clearly, cooperation can only be sustained among a limited number of agents, but exactly how many depends on costs, the discount rate, and the productivity of the stock. Time deviation accommodates more players than effort deviation, the more so the higher the cost. The higher the discount rate, the fewer are the agents among whom cooperation can be sustained, as expected. It is not always the case that more agents can be accommodated in the cooperative solution the higher the cost of fishing; there is a tendency in this direction, but beyond a certain level of costs the critical number of agents falls in the case of a high growth rate of the stock (a = 1). There is a certain tendency that a more productive stock (higher a) would accommodate more agents, but this does not occur for effort deviation and high costs.

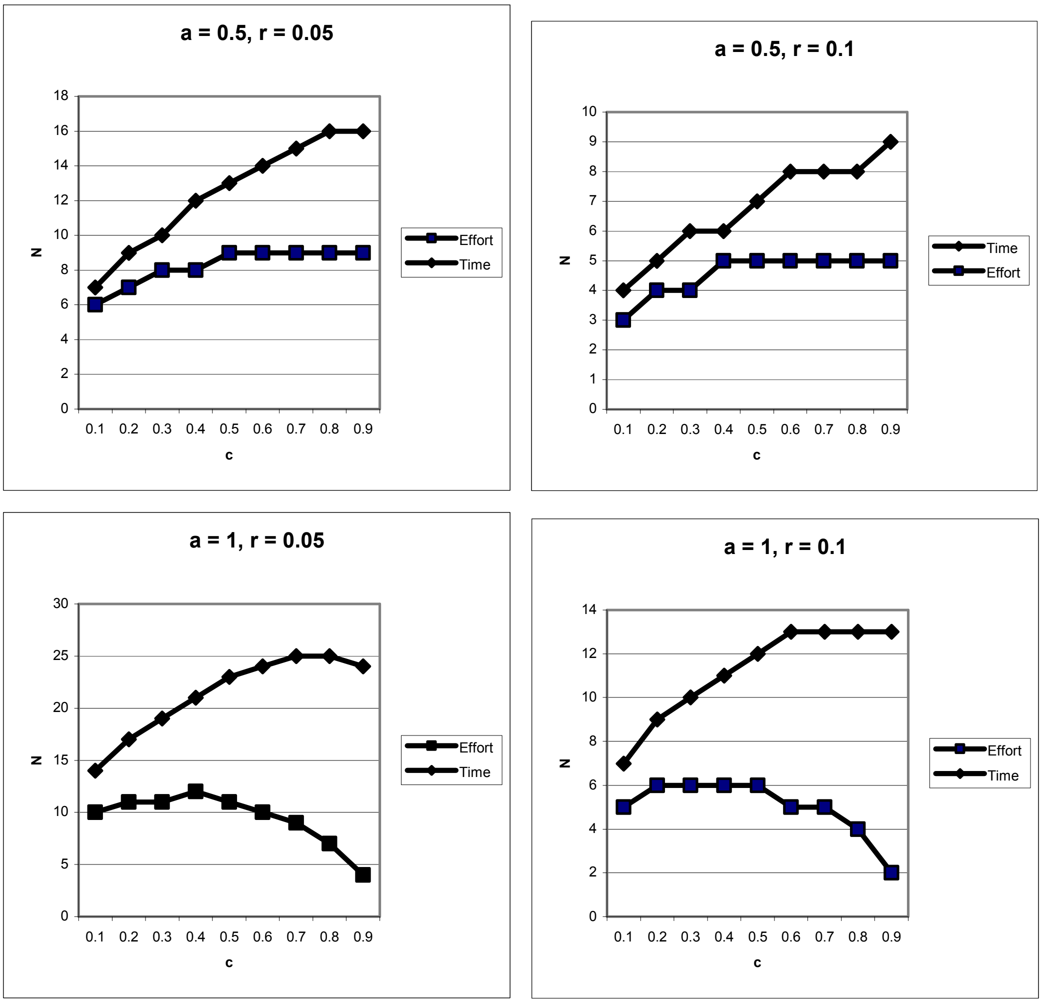

Figure 1: Maximum number of participants consistent with a cooperative solution.

4. LIMITS TO CAPACITY

The deviations considered above implicitly assumed that there is sufficient fishing capacity to reduce the stock to the break-even level. As we shall see in this section, this excess capacity could be quite large, and perhaps unrealistically large. In this section we consider how limited excess capacity affects the possibilities of maintaining a cooperative solution.

Consider first the time deviation. Suppose fishing goes on for a fraction γ of the maximum available fishing time. If the deviating player continues fishing as long as possible, he will be able to reduce the stock in the period of deviation ($t = 0$) to

$$(16) \qquad S_0^* = S^o \exp\left(-\frac{(1/\gamma - 1)E^o}{N}\right)$$

E^o is the effort applied in the cooperative solution, of which each player has $1/N$-th. The deviant player will continue fishing until he either runs up against the time constraint or has depleted the stock to the break-even level.

In the next period all bars are off, and the other players will fish for as long as possible. If all have the same capacity, the total effort will be E^o/γ, or less if this would deplete the stock below the break-even level. In the first period after deviation the stock will be reduced to

$$S_1^* = \max\left[c/p, X_1 \exp\left(-E^o/\gamma\right)\right] \tag{17}$$

and so on, until the break-even level has been reached.

We shall now take into consideration that it may not be necessary to punish the deviant player by keeping the stock at the break-even level indefinitely. Denote the length of the punishment period by T, which includes the time (τ) it takes to drive down the stock to the break-even level. After this, the players may agree to resume cooperation. Since the stock has been depleted, they will have to cease fishing for some time to rebuild the stock. Denote the time it takes to rebuild the stock by Δ. The payoff (v^*) for the deviating agent, taking all this into account, is

$$\begin{aligned}
v^* = {} & \frac{1}{N}\left\{pG\left(S^o\right) - c\left[\ln\left(G(S^o)+S^o\right) - \ln S^o\right]\right\} + p\left(S^o - S_0^*\right) - c\left(\ln S^o - \ln S_0^*\right) \\
& + \frac{1}{N(1+r)}\left\{p\left(G\left(S_0^*\right) + S_0^* - S_1^*\right) - c\left[\ln\left(G\left(S_0^*\right) + S_0^*\right) - \ln S_1^*\right]\right\} \\
& + \ldots\ldots + \frac{1}{N(1+r)^\tau}\left\{p\left(G\left(S_{\tau-1}^*\right) + S_{\tau-1}^* - c/p\right) - c\left[\ln\left(G\left(S_{\tau-1}^*\right) + S_{\tau-1}^*\right) - \ln(c/p)\right]\right\} \\
& + \frac{(1+r)^{-\tau}\left[1-(1+r)^{-T+\tau}\right]}{rN}\left\{p\left(G(c/p)\right) - c\left[\ln\left(G(c/p)+c/p\right) - \ln(c/p)\right]\right\} \\
& + \frac{1}{N(1+r)^{T+\Delta}}\left\{p\left(G\left(S_{T+\Delta-1}\right) + S_{T+\Delta-1} - S^o\right) - c\left[\ln\left(G\left(S_{T+\Delta-1}\right) + S_{T+\Delta-1}\right) - \ln S^o\right]\right\} \\
& + \frac{(1+r)^{-(T+\Delta)}}{rN}\left\{p\left(G\left(S^o\right)\right) - c\left[\ln\left(G\left(S^o\right) + S^o\right) - \ln S^o\right]\right\}
\end{aligned} \tag{18}$$

The criterion for maintaining cooperation is $v^o = V^o/N > v^*$. Let $c = 0.3$, $a = 0.05$, $p = 1$, and $r = 0.05$. This gives $S^o = 0.6$ and a steady state catch of 0.12, and an annual steady state profit of 0.0653. The initial stock in the cooperative solution is $S^o + G(S^o) = 0.72$ while the break-even level is 0.3. A very substantial excess capacity would be needed to reduce the stock to the break-even level, especially with the Schaefer production function, which implies diminishing returns to effort as the stock is depleted. For example, with two players of equal size, the fishing time would have to be about 12 percent of the maximum available time to give one player the opportunity to reduce the stock to the break-even level over just one period.[6] With more players where all have the same capacity, this fraction would have to be lower still.

From Figure 1 we see that, in this case, 10 players could be accommodated in a cooperative solution, on the assumption that there is enough time available for one player to reduce the stock to the break-even level (time deviation). This number is significantly higher if we put realistic restrictions on the time and capacity available to reduce the stock. Figure 2 shows

[6] This is given by Equation (16), with E^o set high enough to give $S_0^* = c/p$.

how the necessary punishment time for different numbers of players depends on the fraction of available fishing time utilized (γ) in the cooperative solution. For fishing that utilizes as little as a quarter of the available time, more than 30 players could be accommodated in a cooperative solution with only 4 years of "punishment" where all fish down to a break-even stock level (and wait for 4 years for the stock to recover after the punishment phase is over). As the fraction of fishing time falls to 1/10 or 1/12 a much longer punishment period will be needed, but 30 or more players could still be accommodated in a cooperative solution.

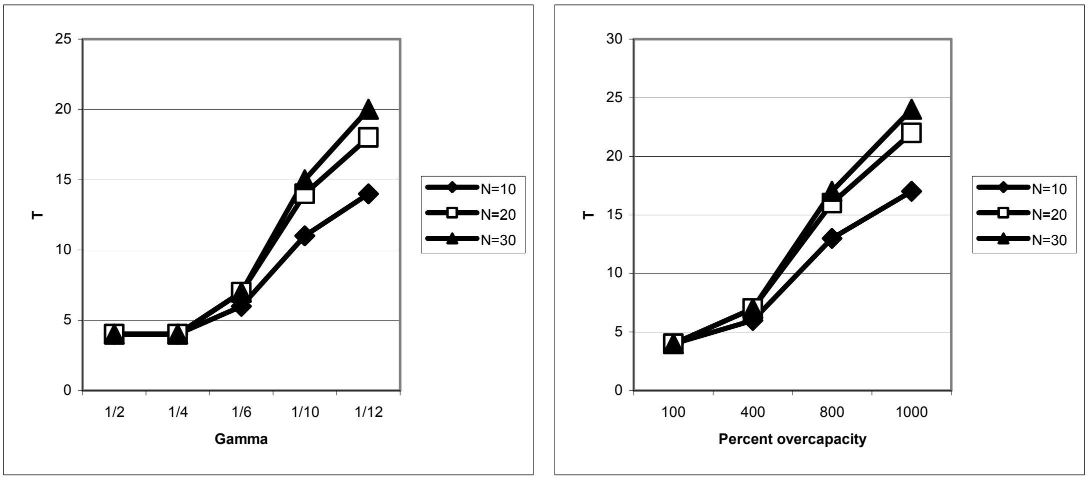

Figure 2: Length of punishment necessary to accommodate 10, 20 and 30 players in a cooperative solution, with a time (left panel) versus effort (right panel) deviation.

Figure 2 also shows the length of the necessary punishment period. The conclusion emerging from this is not very different. With effort deviation, 8 players could be accommodated in a cooperative solution when there were no restrictions on the available fishing capacity (cf. Figure 1), but with such restrictions many more players can be accommodated. Figure 2 shows excess capacity of up to 10 times what would be needed in the cooperative solution, and even here more than 30 players can be accommodated. The necessary punishment phase is less than 10 years with an overcapacity of up to 400 percent, and although it increases quickly as overcapacity rises further it is still finite with 30 players.

The dynamics of profit flow under the effort deviation are slightly different from what obtains under the time deviation. In the optimal solution, the total effort is

(19) $$E^o = NkK\overline{T}$$

where k is the fraction of capacity that the players use, and $\overline{T}$ is the length of the fishing season, assumed to be fully used. If one agent begins to fish with all his capacity, effort will be

(20) $$E_0^* = \left[\left(N-1\right)kK + K\right]T \, , \; T \le \overline{T}$$

with $T < \overline{T}$ if the stock is reduced to its break-even level before the fishing season is over. The stock left behind after fishing will be

(21) $S_0^* = \max\left[c/p, X_0 \exp\left(-E_0^*\right)\right]$

From the next period on, the other agents fish with all their capacity, so that

(22) $E_1^* = NKT\,,\ T \le \bar{T}$

and

(23) $S_1^* = \max\left[c/p, X_1 \exp\left(-E_1^*\right)\right]$

It may take several periods to reduce the stock to the break-even level. After the necessary punishment phase is over, the players may resume cooperation, after allowing the stock to recover. The payoff for the deviant player is a slight modification of (18):

$$
\begin{aligned}
v^* = {} & \frac{E^d}{E^d + E^{-d}}\left\{p\left[S^o + G\left(S^o\right) - S_0^*\right] - c\left[\ln\left(G(S^o) + S^o\right) - \ln S_0^*\right]\right\} \\
& + \frac{1}{N(1+r)}\left\{p\left(G\left(S_0^*\right) + S_0^* - S_1^*\right) - c\left[\ln\left(G\left(S_0^*\right) + S_0^*\right) - \ln S_1^*\right]\right\} \\
& + \ldots\ldots + \frac{1}{N(1+r)^\tau}\left\{p\left(G\left(S_{\tau-1}^*\right) + S_{\tau-1}^* - c/p\right) - c\left[\ln\left(G\left(S_{\tau-1}^*\right) + S_{\tau-1}^*\right) - \ln\left(c/p\right)\right]\right\} \\
& + \frac{(1+r)^{-\tau}\left[1 - (1+r)^{-T+\tau}\right]}{rN}\left\{p\left(G\left(c/p\right)\right) - c\left[\ln\left(G\left(c/p\right) + c/p\right) - \ln\left(c/p\right)\right]\right\} \\
& + \frac{1}{N(1+r)^{T+\Delta}}\left\{p\left(G\left(S_{T+\Delta-1}\right) + S_{T+\Delta-1} - S^o\right) - c\left[\ln\left(G\left(S_{T+\Delta-1}\right) + S_{T+\Delta-1}\right) - \ln S^o\right]\right\} \\
& + \frac{(1+r)^{-(T+\Delta)}}{rN}\left\{p\left(G\left(S^o\right)\right) - c\left[\ln\left(G\left(S^o\right) + S^o\right) - \ln S^o\right]\right\}
\end{aligned}
\tag{18'}
$$

5. CAPACITY COST

The previous discussion has assumed implicitly that there is excess capacity available at no cost. How would the results be affected if we take into account that additional fishing capacity may have to be built at some cost? There are two aspects to be considered. First, the deviant player must invest in additional capacity to deplete the stock to the break-even level and to realize the short term gain that goes with it. Second, the other players must invest in additional capacity to maintain their share of the catch value. There will be situations where it would not pay for the other players to invest in additional capacity to maintain their share of the catch, in which case the gains for the deviant player would be all the greater and the incentives to deviate stronger, and those who deviate first would realize a gain at the expense of the laggards.

Although effort deviation is not unambiguously more profitable than time deviation, it turned out to be so in the examples above, and hence we will consider capacity buildup for the purpose of effort deviation. Consider again a situation where all players are identical and have just enough capacity to take the optimum sustainable yield $G(S^o)$. The total effort necessary to realize this catch is

$$E^o = \ln\left(S^o + G(S^o)\right) - \ln\left(S^o\right) \tag{24}$$

of which each contributes $1/N$. Now suppose that one of the players invests in additional capacity to acquire a greater share of the stock. Suppose that this is just sufficient to reduce the stock to the break-even level over the same time spent fishing as before effort was expanded and the optimum sustainable yield was being taken. This makes the capacity increase proportional to the increase in effort and is also the minimum cost capacity expansion necessary to accomplish the said reduction in the stock.

The effort necessary to reduce the stock to the break-even level is

$$E^* = \ln\left(S^o + G(S^o)\right) - \ln\left(S^*\right) \tag{25}$$

so the effort expansion that the deviant player will undertake is

$$\Delta E^d = E^* - E^o \tag{26}$$

The maximum capacity cost that makes this expansion worth while is equal to the realized gain divided by the capacity expansion. The realized gain is

$$\Delta v^d = \frac{E^* - \left(N-1\right)E^o / N}{E^*}\pi^d - \frac{\pi^o}{N} + \frac{\pi^* - \pi^o}{rN} \tag{27}$$

where

$$\pi^d = p\left[S^o + G\left(S^o\right) - S^*\right] - c\left[\ln\left(S^o + G\left(S^o\right)\right) - \ln S^*\right] \tag{28}$$

on the assumption that the other players retaliate and expand their effort on the same scale as the deviant player. The said maximum capacity cost making the deviation worth while is

$$C^d = \frac{\Delta v^d}{\Delta E^d} \tag{29}$$

But would retaliation by the other players be worth while? It would, at least to an extent, if the derivative of their payoff function is greater than the unit capacity cost. In the new equilibrium with the stock at the break-even level, the payoff of a non-deviant player is

$$v^{j\neq d} = \frac{E^{j\neq d}}{\sum E}\frac{\pi^*}{r} \tag{30}$$

giving

(31) $$\frac{\partial v^{j\neq d}}{\partial E^{j\neq d}}=\frac{\sum_{i\neq j}E^{i}}{\left(\sum E\right)^{2}}\frac{\pi^{*}}{r}$$

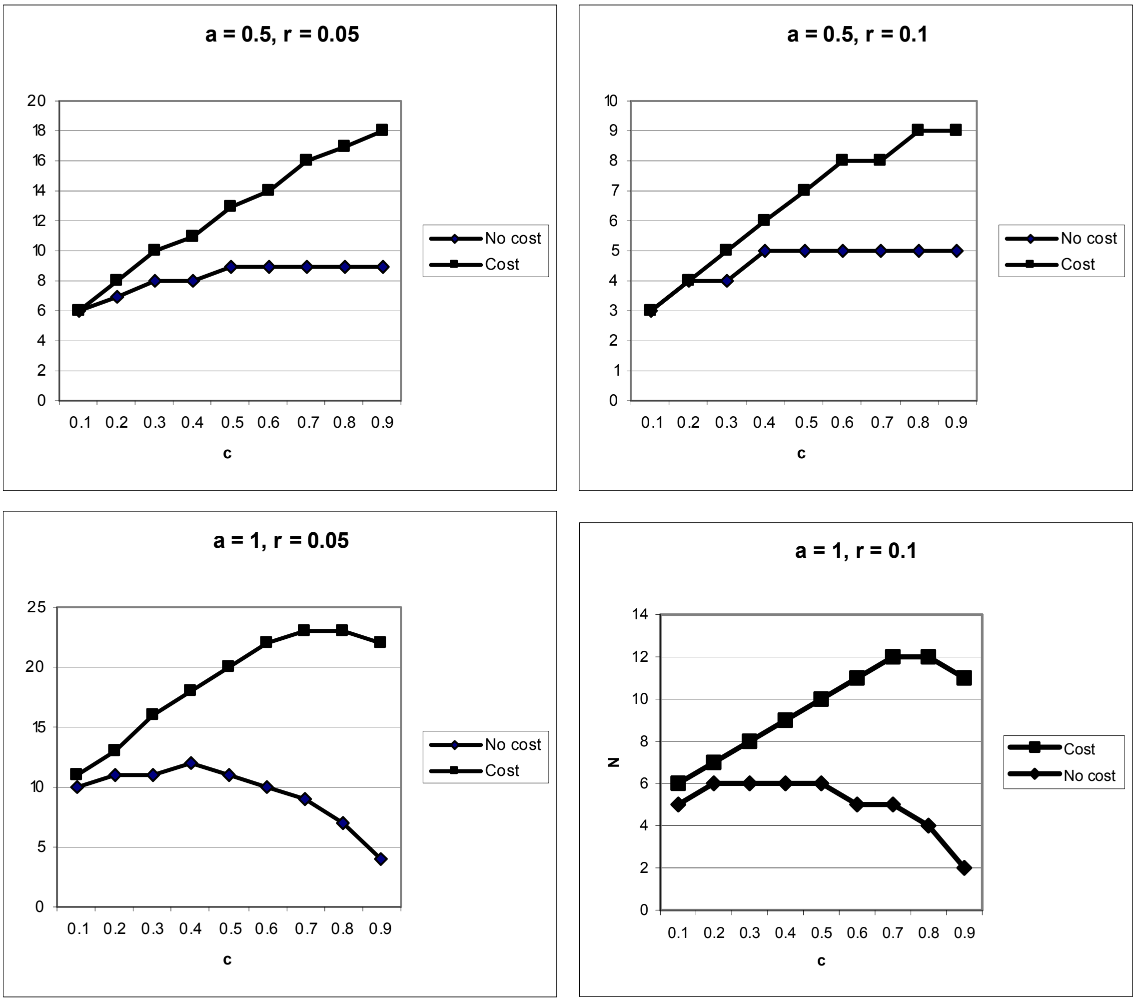

Figure 3: Critical number of players with and without capacity costs.

If $\frac{\partial v^{j\neq d}}{\partial E^{j\neq d}} > C^{d}$ it would be more profitable for the non-deviant players to expand their effort at the margin, in response to the deviation, than it would be to deviate. The relative size of the two terms depends on the number of players, and we can find the critical number of players as the number which reverses the inequality. Figure 3 shows this number together with the number that was obtained ignoring costs and capacity constraints. We see that with the exception of low operating cost of effort (*c*), the number of players compatible with a cooperative equilibrium is higher when capacity costs are taken into account, but still somewhat limited (the highest number occurring is 23).

6. COST HETEROGENEITY

If operating costs differ among the players, this will make deviation more profitable for low cost agents. The viability of the cooperative solution could be quickly eroded as cost differentials increase. Here we shall consider a model with a single low cost agent and N - 1 high cost agents. We shall consider the case with time deviation, because whichever form the deviation takes, the low cost player will be able to fish profitably for a longer period than the high cost players, his break-even stock level being lower. This makes the deviation from cooperation more profitable than otherwise for the low cost player. Furthermore, because of the cost differential, the low cost player could possibly exclude the high cost players from the fishery by depleting the stock to a level that is low enough for the returning stock to be below the break-even level for the high cost players. If that level is above the break-even level for the low cost player, he would not need to deplete the stock that much. This would further raise the payoff from deviation, partly because the competing high cost player could be excluded altogether and partly because the low cost player would not have to deplete the stock as much as otherwise.

The stock level that excludes the high cost players ($S^{\#}$) is given by

(32) $$S^{\#} + G\left(S^{\#}\right) = c_h / p$$

where c_h is the cost per unit of effort for the high cost agents. With c_l being the cost per unit of effort for the low cost agent, the level to which he will ultimately fish down the stock is

(33) $$S^{*} = \max\left[c_l / p, S^{\#}\right]$$

How quickly this will happen depends on the fishing capacity of the low cost agent. Note also that the fishing in each period can be divided into two phases, one in which all fish simultaneously and one that occurs after the stock has been depleted below the break-even level of the high cost agents (c_h/p) and the low cost agent fishes alone (both phases need not always exist simultaneously). The stock left at the end of the first phase of each period $S^{*}_{t,1}$ will be whichever is greatest, the break-even level for the high cost agents, or the level determined by the low cost agent's capacity:

(34) $$S^{*}_{t,1} = \max\left(S^{*}_{t}, c_h / p\right)$$

The second phase will occur when the low cost agent is able to deplete the stock below the break-even level of the high cost agents. The stock left after fishing at the end of the second phase will be given by

(35) $$S^{*}_{t,2} = \max\left(S^{*}_{t}, S^{\#}, c_l / p\right)$$

An additional question concerns what determines the optimal stock, S^{o}. The high cost agents and the low cost agent will not agree on that, because their cost levels are different. We shall use the low cost agent's cost as a reference point, because this would make the low cost agent less willing to deviate from the optimal solution. We then get the deviating agent's payoff as a modification of (18):

$$
\begin{aligned}
v^* = {} & \frac{1}{N}\left\{pG\left(S^o\right) - c_l\left[\ln\left(G(S^o) + S^o\right) - \ln S^o\right]\right\} + p\left(S^o - S_0^*\right) - c_l\left(\ln S^o - \ln S_0^*\right) \\
& + \frac{1}{N(1+r)}\left\{p\left(G\left(S_0^*\right) + S_0^* - S_{1,1}^*\right) - c_l\left[\ln\left(G\left(S_0^*\right) + S_0^*\right) - \ln S_{1,1}^*\right]\right\} \\
& + \frac{1}{(1+r)}\left\{p\left(S_{1,1}^* - S_{1,2}^*\right) - c\left[\ln S_{1,1}^* - \ln S_{1,2}^*\right]\right\} \\
& + \ldots.. + \frac{1}{N(1+r)^\tau}\left\{p\left(G\left(S_{\tau-1}^*\right) + S_{\tau-1}^* - S_{\tau,1}^*\right) - c_l\left[\ln\left(G\left(S_{\tau-1}^*\right) + S_{\tau-1}^*\right) - \ln S_{\tau-1,1}^*\right]\right\} \\
& + \frac{1}{(1+r)^\tau}\left\{p\left(c_h / p - S^*\right) - c\left[\ln c_h / p - \ln S^*\right]\right\} \\
& + \frac{(1+r)^{-\tau}\left[1-(1+r)^{-T+\tau}\right]}{rN}\left\{p\left(G\left(S^*\right)\right) - c_l\left[\ln\left(G\left(S^*\right) + S^*\right) - \ln\left(c_h / p\right)\right]\right\} \\
& + \frac{(1+r)^{-\tau}\left[1-(1+r)^{-T+\tau}\right]}{r}\left\{p\left(c_h / p - S^*\right) - c_l\left[\ln c_h / p - \ln S^*\right]\right\} \\
& + \frac{1}{N(1+r)^{T+\Delta}}\left\{p\left(G\left(S_{T+\Delta-1}\right) + S_{T+\Delta-1} - S^o\right) - c\left[\ln\left(G\left(S_{T+\Delta-1}\right) + S_{T+\text{A}-1}\right) - \ln S^o\right]\right\} \qquad (18") \\
& + \frac{(1+r)^{-(T+\Delta)}}{rN}\left\{p\left(G\left(S^o\right)\right) - c\left[\ln\left(G\left(S^o\right) + S^o\right) - \ln S^o\right]\right\}
\end{aligned}
$$

Table 1: The number of players with unlimited capacity (N_∞) and the maximum number of players with 100% overcapacity (max N) compatible with a cooperative solution. Infinite punishment period, season length ½ of maximum, time deviation. Cost of the high cost players (c_h). Cost of low cost player: c_l = 0.3.

c_h	N_∞	$1/\gamma$ - 1	max N
0.3	10	1	∞
0.325	9	1	42
0.35	6	1	11
0.375	4	1	6
0.4	3	1	3
0.45	2	1	2

It turns out that the critical number of players that can be accommodated in a cooperative solution is very sensitive to the cost differential between the high cost players and the low cost player. Table 5 shows results for c_l = 0.3 and successively rising cost (c_h) of the high cost players. With c = 0.3 for all, 10 players can be accommodated in the cooperative solution when there are no limits on capacity, and an unlimited number if the capacity is just twice that needed and stays that way for ever. The number that can be accommodated in the case of unlimited capacity falls quickly as c_h rises and reaches 2 when c_h = 0.45. The maximum number that can be accommodated with capacity twice what is needed (a fishing season that lasts only half the available time) also falls quickly, from infinity to 40 when c_h = 0.325, and reaches the number for unlimited capacity already at c_h = 0.4.

CONCLUSION

This paper has shown that a cooperative solution in a game of a shared fish stock can be sustained only with a limited number of players. This is particularly the case if there are no constraints on the available fishing capacity or the time available for excess fishing. If we assume that overcapacity is only moderate, such that the total capacity is only two or three times what would be needed, it becomes possible to support many more participants in the cooperative solution. But there is limited comfort in this. We also showed that there could be incentives to build up a capacity that could come perilously close to limiting the number of players compatible with a cooperative solution to something comparable to the number of countries sharing some fish stocks, to say nothing of the number of countries (flag states) with a potential interest in high seas fisheries.

The most damaging case for the cooperative solution is the possibility that different nations have different fishing costs. This, needless to say, is highly likely to be the case. Only rather minor cost differentials are sufficient to limit the number of participants consistent with the cooperative solution to a number that can be counted with the fingers on one hand.

In the light of this, it is not surprising that cooperative solutions in high seas fisheries are difficult to achieve. That conclusion is supported by other approaches, such as looking at coalitions in non-cooperative games (see, e.g., Lindroos and Kaitala, 2000, and Pintassilgo, 2003).

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