JOURNAL OF ENVIRONMENTAL ECONOMICS AND MANAGEMENT **32**, 309–322 (1997)
ARTICLE NO. EE970971

Fishing as a Supergame

Rögnvaldur Hannesson

The Norwegian School of Economics and Business Administration, Helleveien 30, N-5035 Bergen-Sandviken, Norway

Received February 6, 1996; revised May 15, 1996

This paper considers how cooperative solutions to games of sharing fish resources can be supported by threat strategies. With highly mobile fish stocks, the number of agents compatible with a cooperative self-enforcing solution is not very high for reasonable values of the discount rate, but sensitive to changes in the discount rate and costs and to cost heterogeneity. With migrating stocks, where growth and reproduction depend on how much all agents leave behind after harvesting, the likelihood of a cooperative, self-enforcing equilibrium is increased. With a dominant player and a competitive fringe the rents and optimum stock level of the dominant player fall quickly as the share of the competitive fringe increases.

1. INTRODUCTION

Exploitation of renewable resources such as fish stocks shared by a limited number of agents involves strategic choices. Should the agents cooperate and maximize their aggregate returns, or is cooperation a futile exercise undertaken by the naive, who will be outsmarted by the realistic? There exists by now a voluminous literature on this subject. Much of this literature was inspired by the international disputes over fishing limits in the 1970s and the deliberations of the third United Nations Conference on the Law of the Sea 1973–1982 which endorsed the 200-mile exclusive economic zone. Two early papers in this genre are Munro [11] and Levhari and Mirman [9]. Recently Fischer and Mirman [2, 3] have extended the analysis to interacting species. Three of these papers compare Nash equilibria and global optima while Munro is concerned with bargaining solutions in cooperative games. All these papers deal with the case of two agents, which is true of most of the literature on game theory and fisheries; few authors have considered explicitly the importance of the number of agents for obtaining a cooperative solution. An exception is Clark [1] who does not, however, consider the implications of threat strategies in repeated games. Hämäläinen *et al*. [6] do so, but again limit themselves to the case of two agents.

The motivation to explore the importance of the number of agents is provided by the fact that many important fish stocks enclosed by the 200-mile limit are shared by two or more coastal states. What is the likelihood that they will cooperate in setting the rate of exploitation of the stocks and how does it depend on the number of states sharing a stock? A further motivation is provided by the straddling of some fish stocks outside the 200-mile limit where they are accessible by fleets of any nationality. What are the chances of cooperation under those circumstances, or more to the point perhaps, how will the strategy of the coastal state(s) controlling the main part of a stock be affected by this competition?

0095-0696/97 $25.00

This latter case is a topical one. In 1993 the UN convened a conference on the exploitation of straddling and highly migratory fish stocks. The conference was concluded in August 1995 with an agreement that authorizes regional organizations to manage fisheries outside the 200-mile limit. All who fish in a given area will have to abide by the rules agreed by the relevant organization. It is unclear, however, what if anything limits the membership of such organizations; the agreement says only that member nations must have a "real interest" in fishing in the area. Neither is it clear how decisions will be taken, whether this will be by majority vote, a qualified majority, or a consensus. Last but not least, it is unclear what sanctions can and will be applied to those who do not cooperate.

In this paper we consider how critical the number of agents sharing a fish stock is for realizing the cooperative (globally optimal) solution. The problem is formulated as a repeated game of an infinite duration (a supergame). We begin by considering a game of N identical agents. Then we look into the importance of cost differences among agents. In both these formulations agents are assumed to exploit a truly common stock; i.e., the density of the stock will be the same for all. We then consider a somewhat different problem which may be more relevant for countries sharing a fish stock. Each agent is assumed to exploit a certain portion of the stock being accessible for exploitation only in that agent's territory but nevertheless linked to the remainder of the stock through a common growth function. The cooperative solution is defined as the global optimum, while the noncooperative solution is the one where each agent realizes his individual optimum without taking into account the stock growth externality. Finally we look at a case meant to reflect the straddling stock situation where a dominant agent maximizes his profits, taking into account a fringe of exploiters who have access to a portion of the stock outside his territory. The focus here is on the efficiency losses vis-à-vis the global optimum.

2. THE BASIC MODEL

Assume that the growth of the fish stock is determined by how much is left behind after harvesting; i.e., the stock at the beginning of period t is a function $G(S_{t-1})$, where S_{t-1} is the stock left behind after harvesting in period $t-1$ (the size of the stock left behind will be referred to as the abandonment level). Ignoring natural mortality of the stock while it is being fished, the amount caught in period t will be $G(S_{t-1}) - S_t$. At a given price (p) the revenue (R) obtained in period t will be

$$R_t = p\left[G(S_{t-1}) - S_t\right]. \tag{1}$$

Assume that the marginal cost of fish is inversely proportional to the size of the stock at any point in time.[1] The total cost (C) in period t will then be

$$C_t = \int_{S_t}^{G(S_{t-1})} \frac{c}{x}\,dx = c\left[\ln G(S_{t-1}) - \ln S_t\right], \tag{2}$$

[1] This cost function obtains if the cost per unit of fishing effort is constant and the catch per unit of effort is proportionate to the size of the exploited stock. The latter obtains if the stock is always evenly distributed over a given area. While popular and not unreasonable, this is obviously a special case. The emphasis here is on obtaining numerical results, which makes it necessary to use a simple but not unreasonable cost function. For a further discussion, see [7].

where c is a cost parameter. Since the quantity caught (Q) is $Q = G - S$, with G being given at the beginning of each period, this function has the usual properties $C_Q = -C_S > 0$ and $C_{QQ} = -C_{SS} > 0$ (subscripts denote derivatives).

The present value (V) of fishing rent ($R - C$), for an infinite time horizon, is

$$V = \sum_{t=0}^{\infty} \delta^t \{p[G(S_{t-1}) - S_t] - c[\ln G(S_{t-1}) - \ln S_t]\}. \tag{3}$$

Maximizing V with respect to S_t gives the first order condition[2]

$$-\left(p - c/S_t^0\right) + \delta\left[p - c/G\left(S_t^0\right)\right]G'\left(S_t^0\right) = 0, \tag{4}$$

where $\delta = 1/(1+r)$ is the discount factor, r being the discount rate, with G' denoting the first derivative of G and S^0 the optimum value of S.

As an illustration in numerical calculations below we shall use the discrete variant of the logistic growth function

$$G(S) = S[1 + a(1 - S/K)], \tag{5}$$

where a and K are parameters (intrinsic growth rate and carrying capacity, respectively). This gives

$$G'(S) = 1 + a(1 - 2S/K). \tag{6}$$

3. COOPERATIVE EQUILIBRIUM: IDENTICAL AGENTS

Suppose there are N identical agents who share a fish stock. Suppose further that they plan to harvest the stock for an indefinite period of time. If they cooperate in realizing the optimal solution (which is identical from everybody's perspective) each will get $1/N$th of the total profits in each period. If one of them deviates from the optimal solution he will get more, as long as the deviation has not been discovered and punished. Assume that deviation would be detected after one period and that the other agents then would retaliate by fishing down the stock in each period until further depletion becomes unprofitable, i.e., until the marginal cost of fish caught has risen to equal the price (cf. Eq. (2)). This is in fact the best strategy they could follow, as long as the deviating agent depletes the stock to the level where fishing becomes unprofitable (an alternative trigger strategy will be commented upon below). In view of the above cost and revenue functions (Eqs. (1) and (2)), the abandonment level of the stock (S^*) would then be

$$S^* = c/p. \tag{7}$$

[2] The same first order condition also obtains for a finite time horizon except for the last period where the optimal abandonment level is $S^* = c/p$ when the stock beyond the horizon has no value. If the initial stock is less than the optimal stock it will be necessary to leave it unfished for one or more periods, until $G(S_{t-1}) > S^0$.

For an infinite time horizon, the present value of the cooperative strategy (V^0) for a typical agent is

$$V^0 = \frac{\pi^0}{N}\frac{1}{1-\delta}, \tag{8}$$

where

$$\pi^0 = p\left[G(S^0) - S^0\right] - c\left[\ln G(S^0) - \ln S^0\right] \tag{9}$$

and S^0 is the abandonment level of the stock along the optimal (cooperative) stationary path.

The present value of the payoff for an agent that deviates from the cooperative solution and is then punished by all other agents playing noncooperatively forever is

$$V^d = \frac{\pi^0}{N} + \pi^d + \frac{\pi^*}{N}\frac{\delta}{1-\delta}, \tag{10}$$

where

$$\pi^d = p(S^0 - S^*) - c(\ln S^0 - \ln S^*) \tag{11}$$

and

$$\pi^* = p\left[G(S^*) - S^*\right] - c\left[\ln G(S^*) - \ln S^*\right]. \tag{12}$$

In the first period, the defector gets the same profit as in the cooperative solution, as all other participants play cooperatively, and in addition he gets the profit of driving the stock down to the noncooperative abandonment level. In the second and all later periods he will be punished by all other agents playing noncooperatively and gets only the profit obtained in the noncooperative solution (cf. Eq. (7)).

If defection is not profitable, $V^0 > V^d$, which implies

$$N < \frac{\delta}{1-\delta}\frac{\pi^0 - \pi^*}{\pi^d}. \tag{13}$$

As $\delta \to 1$ the right-hand side of (13) approaches infinity and defection will never be profitable; the losses from being punished will always outweigh the temporary gains of defecting. For a positive discount rate ($\delta < 1$) the temporary gains of defecting may outweigh the long term loss of playing noncooperatively rather than cooperatively. How likely this is depends on N, the number of players. The gains from defecting accrue to the defector while the losses from playing noncooperatively rather than cooperatively are shared by all participants. The temptation of defecting therefore becomes greater the more participants there are. Specifying the parameters of the growth equation $G(S)$ makes it possible to find the critical value of N for alternative values of the discount factor. A selection of results is presented in Fig. 1.

The values of the parameters a, c, and δ in Fig. 1 are meant to reflect a realistic range. The parameter a is the maximum relative rate of growth (cf. Eq. (6)). Figure 1 shows solutions for two alternative values of a, 20 and 50%. The ratio c/S shows the marginal cost of fish (cf. Eq. (2)). The maximum size of the stock is K (cf. Eq.

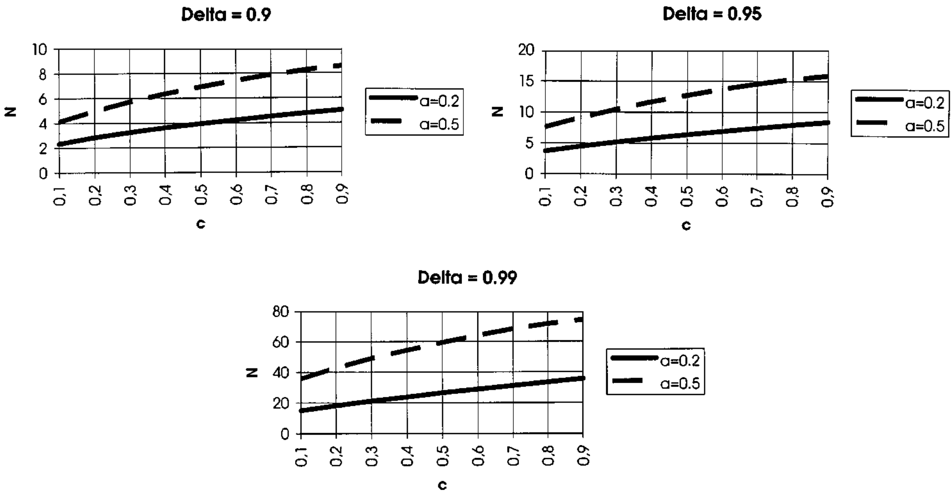

FIG. 1. Relationship between the maximum number of players in a cooperative solution and the minimum marginal cost of fish.

(5)), so c/K can be interpreted as the minimum marginal cost of fish, prevailing at the beginning of exploitation of a pristine stock. Since K has been set equal to 1, c shows the lowest marginal cost of fish as a fraction of the pristine stock. The values of c in Fig. 1 range from 0.1 to 0.9. A value of 1 would imply that fishing would never be profitable while a value of 0 would imply no cost of fishing. Finally, the three values of δ in Fig. 1 imply discount rates of approximately 1, 5, and 11%.

Figure 1 indicates that N, the maximum number of participants in the fishery compatible with a self-enforcing cooperative solution, will be highly sensitive to the discount factor and the cost of fishing. As already mentioned, a higher discount rate (lower value of δ) makes the cooperative solution less likely. For $c = 0.1$ and $a = 0.2$ N is only 2 when $\delta = 0.9$, but rises to 3 and 15, respectively, as δ increases to 0.95 and 0.99. A higher marginal cost of fish makes it more likely that the cooperative solution will prevail; the abandonment level of the stock in the noncooperative solution will be higher and the gains from defection smaller. This is readily seen from the figure; as c increases from 0.1 to 0.9 N approximately doubles. Finally, raising a from 0.2 to 0.5 approximately doubles N for any given c.

If we interpret N as the number of countries which share a resource and have the necessary control over their fishing fleets, the results in Fig. 1 are not too discouraging. Whenever stocks are fully contained within the 200-mile zone but migrate between different national zones, the number of countries with access rights is usually highly restricted. Quite often there are just two countries sharing a stock, like Canada and the United States on George's Bank, while several countries share the stocks of the North Sea. A discount rate of the order of 5–10% appears realistic and would accommodate a cooperative solution among a few countries.

For the case of stocks located outside the 200-mile zone the conclusion is much more pessimistic. The number of potential exploiters of such stocks is high, as witnessed by the fact that some boat owners use flags of convenience when fishing on the high seas. Up to now this number has in fact been indefinite, as international law has not recognized any mechanism to limit access to fishing outside the 200-mile zone. It remains to be seen whether the agreement reached by the UN conference on highly migratory and straddling fish stocks will change this.

The results in Fig. 1 in part corroborate a tendency which Mesterton-Gibbons [10] has termed ‘‘comedy of the commons,’’ namely that cooperation can arise spontaneously and be self-enforcing if the commons are sufficiently unproductive. In Fig. 1 we see that the number of participants that can be accommodated in a self-enforcing cooperative solution increases with the cost of exploitation. However, the more productive stock (the one with an intrinsic growth rate of 0.5) accommodates more participants in a self-enforcing cooperative solution than the less productive stock, which would seem to contradict the comedy of the commons. The reason why the more productive stock accommodates more participants in a self-enforcing cooperative equilibrium is that the losses from playing noncooperatively are greater, being associated with foregone potential growth, while the gains from defecting are due to fishing down the stock in one period.

It is possible to give an alternative interpretation of the results in Fig. 1. These results were derived on the assumption that the punishment of a defector would go on forever. This is unnecessarily heavy handed. The defector might promise to mend his ways, and all participants might be well advised to revert to the cooperative solution. However, in order to be an effective deterrent the punishment must go on for a sufficiently long time to make the cooperative strategy more attractive for a potential defector. To accomplish this the $N - 1$ participants might threaten to play the noncooperative strategy for a finite number of periods. We may ask what is the minimum number of periods (T) in which the noncooperative strategy must be played in order to deter a potential defector. Instead of (10), define $V^d(T)$ as[3]

$$V^d(T) = \frac{\pi^0}{N} + \pi^d + \sum_{t=1}^{T} \delta^t \frac{\pi^*}{N} + \frac{\delta^{T+1}}{1-\delta} \frac{\pi^0}{N}. \tag{10'}$$

An effective punishment requires $V^0 > V^d(T)$, which implies

$$T > \frac{\ln F}{\ln \delta}, \tag{14}$$

where

$$F = 1 - \frac{1-\delta}{\delta} \frac{N\pi^d}{\pi^0 - \pi^*}. \tag{15}$$

As $F \to 0$, the right-hand side of (14) approaches infinity. The value of N which gives $F = 0$ is precisely the same as would make (13) an equality. Hence it is possible to interpret the figures in Fig. 1 as the number of participants that will make it possible to deter a defector by threatening to play the noncooperative strategy for a finite number of periods.

[3] I am grateful to an anonymous referee for pointing this out. Punishment strategies that last for a finite period are discussed in [12], Chapter 8.6.

4. COOPERATIVE EQUILIBRIUM WHEN COSTS DIFFER AMONG AGENTS

The analysis so far has been based on the assumption that all agents have identical cost functions. However, what if some agents are more efficient than others? Such agents might be tempted to "undercut" high cost agents and fish down the stock to a level where the high cost agents are barred from entry.[4] The incentive to do so will be strongest when there are many high cost agents and few low cost agents. Here we shall look at an example with one low cost agent and $N - 1$ high cost agents, with cost parameters c_l and c_h, respectively, but otherwise identical cost functions.

The low cost agent will be able to fish down the stock to a lower abandonment level than the high cost agents without incurring losses. In the noncooperative solution two cases may arise. (i) The low cost agent depletes the stock to the level c_l/p, but since the stock at the beginning of each period is $G(c_l/p)$, the high cost agents can still do some profitable fishing if $G(c_l/p) > c_h/p$. (ii) The cost difference is so great that $G(c_l/p) < c_h/p$. In that case the low cost agent can undercut the high cost agents and exclude them from the fishery altogether. It would not, however, be profitable for the low cost agent to leave behind a smaller stock than that which gives $G(S^*) = c_h/p$ (i.e., exactly undercuts the high cost agents), unless the optimum stock for the low cost agent alone is less than this.

Hence the abandonment level of the stock in a noncooperative equilibrium will be

$$S^* = \max\left[\frac{c_l}{p}, G^{-1}\left(\frac{c_h}{p}\right)\right]. \tag{16}$$

The profit of the low cost agent in a noncooperative play may be split into two parts. The first is the profit of fishing down the stock from $G(S^*)$ to c_h/p. In this phase (which may be nonexistent) the low cost agent gets only $1/N$th of the catch. In the second phase the low cost agent drives the stock further down to S^* and has all this catch to himself. The two parts of the profit of the low cost agent thus are

$$\pi_1^* = p[G(S^*) - c_h/p] - c_l[\ln G(S^*) - \ln(c_h/p)] \tag{17a}$$

$$\pi_2^* = p[c_h/p - S^*] - c_l[\ln(c_h/p) - \ln S^*]. \tag{17b}$$

The gain from defection will be greater than before, because some and possibly all of the catch in the noncooperative equilibrium does not have to be shared with all agents but will be taken by the low cost agent alone. Equation (10) becomes

$$V^d = \frac{\pi^0}{N} + \pi^d + \left[\frac{\pi_1^*}{N} + \pi_2^*\right]\frac{\delta}{1-\delta} \tag{10''}$$

and (13) becomes

$$N < \frac{\delta(\pi^0 - \pi_1^*)}{\delta\pi_2^* + (1-\delta)\pi^d}. \tag{13''}$$

[4] This is what happens in the closed loop solution derived by Clark [1].

The question arises as to what would be the optimum stock level in the cooperative solution, since the high cost agents and the low cost agent will not agree on this. A global optimum would entail fishing by the low cost agent only, with side payments to the high cost agents. If this is not possible, the agents might agree on some mutually acceptable abandonment level of the stock that allows both low cost and high cost agents to make a profit. Here it will be assumed that the cooperative solution is determined with reference to the cost of the low cost agent, as this will minimize the likelihood that the low cost agent will want to defect. Note that this solution does not impose losses on the high cost agents as long as $pS^0 > c_h$.

As before, we can calculate the number of participants accommodated by a self-enforcing cooperative equilibrium (N). A sample of such results is shown in Fig. 2 and compared to the case with cost homogeneity. The dashed curves in Fig. 2 show N when all agents have the same cost (same as in Fig. 1). The solid curves show what happens when one agent has a lower cost parameter (c) than the rest. As the cost of one agent starts to fall below that of the rest N drops quickly, particularly when the cost is high. Note that when the cost is high N is also high, and the losses from ending up in a noncooperative solution are low compared to the gains from defecting, since the losses are spread among all players. This is why it takes only a slight difference in costs to produce a steep fall in N when N is high initially.

The effect of cost heterogeneity is seen to be substantial; it does not take a great difference in costs to reduce N to a number not much higher than two, irrespective of the discount rate, cost level, or productivity of the fish stock. There may be reason, therefore, for less optimism than expressed above for the likelihood of a cooperative solution emerging among a limited number of countries sharing a fish stock.

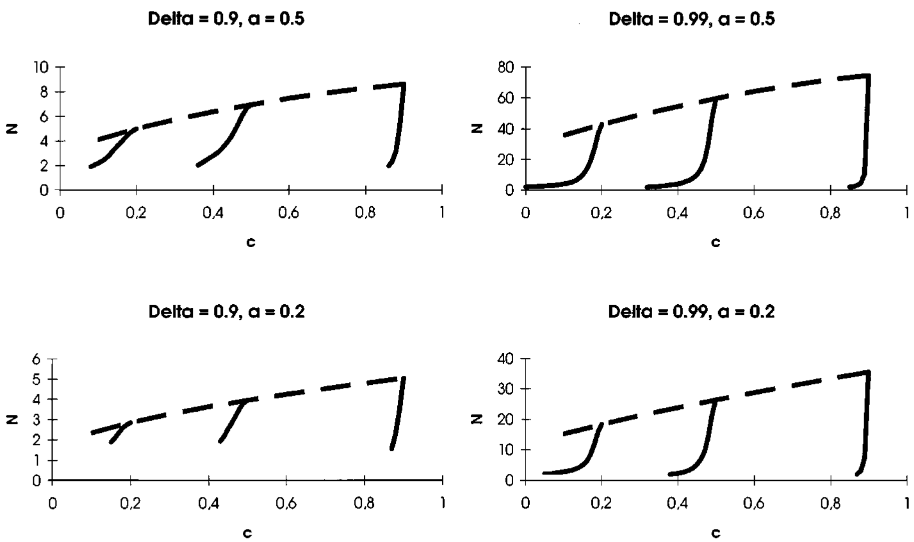

FIG. 2. How the minimum number of players in a cooperative solution depends on the cost difference between a low cost player and high cost players. Dashed line, equal cost for all players.

5. COOPERATIVE EQUILIBRIUM WITH LIMITED MIGRATION OF STOCKS ACROSS BOUNDARIES

In the above examples it was implicitly assumed that the agents fish simultaneously on the same stock or, what amounts to the same thing, that each agent fishes in his own area but that the fish redistribute themselves instantaneously between the areas so that the distribution is always the same in all areas. A more realistic example could be where each agent fishes in his own area and the fish migrate only slowly between areas or visit these areas sequentially with a seasonal pattern.[5] The growth of the stock could still be dependent on the aggregate size of the stock, because of a seasonal pattern of breeding migration or because the eggs and larvae are distributed over the entire habitat of the stock irrespective of where they are spawned.

Here we shall look at a stylized version of this. Let the stock be measured as density, i.e., units of fish per unit area (tonnes per square km, for example). The reason for taking this approach is that the marginal cost of fish depends on the density of the stock and thus indirectly on the size of the stock, provided that the area it occupies does not shrink in proportion to the depletion of the stock. To make the comparison with previous cases easier we define the unit area as the entire area that the stock occupies, assumed always to be of the same size. Assume that the area is divided among N agents. In each period we start with a stock (G) that is uniformly distributed over the area. The amount available for agent i will be $\gamma_i G$, where γ_i is agent i's share of the area where the stock is located.[6] The fish are assumed not to migrate between the agents' subareas during each fishing period, so each agent has full control over the abandonment level of the stock in his area $(\gamma_i S_i)$. After each fishing period the stock grows and redistributes itself randomly over the entire area. This leads to the growth function

$$G(\Sigma\gamma_i S_{i,t-1}),$$

where

$$\Sigma\gamma_i = 1. \tag{18}$$

The growth of the stock depends on what all agents leave behind $(\Sigma\gamma_i S_i)$, and all agents start fishing a stock of the same density at the beginning of each period $[G(\Sigma\gamma_i S_{i,t-1})]$.

The globally optimal solution will be the same as derived above (Eq. (4)). For this solution to be realized, each agent would have to leave behind a stock compatible with the global optimum, and he would get a share in the total profits equal to his share of the area where the stock is located. If, on the other hand, each agent optimizes for himself, the optimum stock to be left behind in period t

[5] The case of sequential fishing is dealt with in [8] and will not be considered here.

[6] The assumption of uniform distribution is unnecessarily strong. All that is required is that the stock always redistribute itself in the same way after each fishing period. The share parameters γ_i will then be constant.

will be given by maximizing a modified version of (3):

$$V_i = \sum_{t=0}^{\infty} \delta^t \gamma_i \{ p[G(\Sigma \gamma_j S_{j,t-1}) - S_{i,t}] - c[\ln G(\Sigma \gamma_j S_{j,t-1}) - \ln S_{i,t}]\}. \quad (19)$$

Note that the profit function is multiplied by γ_i because the stock is measured as density, with the unit area being equal to the entire habitat of the stock.

The first order condition for maximum is

$$-[p - c/G(\Sigma \gamma_j S_j^0)] + \delta \gamma_i G'(\Sigma \gamma_j S_j^0)[p - c/S_i^0] = 0. \quad (20)$$

We shall now define "defection" as optimization of each agent for himself, i.e., choosing the abandonment level which is optimal according to Eq. (20). We denote this by S^* and reserve the notation S^0 for the globally optimal abandonment level. We continue to assume that defection will be discovered after the period in which it occurs. In the period after defection occurs, other agents adjust their harvesting to attain the abandonment level (S^*), so in this case the punishment strategy does not begin to bite until two periods after defection begins. The stock returning at the beginning of the period after defection will be $G(S^0\gamma_{-i} + S^*\gamma_i)$, where the notation "$-i$" means all agents except agent i, the defecting agent. The condition for defection not being profitable is

$$\frac{\pi^0}{1-\delta} > \pi_1^d + \delta \pi_2^d + \frac{\delta^2}{1-\delta}\pi^*, \quad (21)$$

where

$$\pi_i^0 = \gamma_i \{ p[G(\Sigma \gamma_j S_j^0) - S_i^0] - c[\ln G(\Sigma \gamma_j S_j^0) - \ln S_i^0]\} \quad (22a)$$

$$\pi_{1,i}^d = \gamma_i \{ p[G(\Sigma \gamma_j S_j^0) - S_i^0] - c[\ln G(\Sigma \gamma_j S_j^0) - \ln S_i^0]\}$$
$$+ \gamma_i \{ p(S_i^0 - S_i^*) - c(\ln S_i^0 - \ln S_i^*)\} \quad (22b)$$

$$\pi_{2,i}^d = \gamma_i \{ p[G(\Sigma S_j^0 \gamma_{-i} + S_i^* \gamma_i) - S_i^*] - c[\ln G(\Sigma S_j^0 \gamma_{-i} + S_i^* \gamma_i) \text{-ln } S_i^*]\} \quad (22c)$$

$$\pi_i^* = \gamma_i \{ p[G(\Sigma \gamma_j S_j^*) - S_i^*] - c[\ln G(\Sigma \gamma_j S_j^*) - \ln S_i^*]\}. \quad (22d)$$

The expression on the left-hand side of (21) is the present value of playing cooperatively while the expression on the right-hand side is the present value of defecting. In the period when defection occurs the defector gets the extra benefit of reducing the density of the stock in his area to the level S^* (Eq. (22b)). This benefit is, of course, less than in previous cases where the defector could reduce the overall density of the stock, due to its instantaneous migration. At the end of this period the defector is found out and everyone depletes his stock to density S^* from then onward, but the stock emerging at the beginning of the period after defection has not yet reached the long term equilibrium (Eq. (22c)). The noncooperative equilibrium is reached in the second period after defection (Eq. (22d)).

The maximum number of players that can be accommodated in a cooperative equilibrium is defined implicitly by (21). Table I shows some solutions for the case with identical agents ($\gamma_i = 1/N$). In general it is much more likely that a coopera-

TABLE I

Maximum Number of Agents (N) Compatible with Sustaining the Global Optimum as a Cooperative Self-Enforcing Equilibrium ($a = 0.2$)

	$c = 0.1$					$c = 0.05$				
		Global optimum		Individual optimum			Global optimum		Individual optimum	
δ	N	S^0	G^0-S^0	S^*	G^*-S^*	N	S^0	G^0-S^0	S^*	G^*-S^*
0.8	4	0.212	0.0335	0.105	0.0187	2	0.133	0.0231	0.057	0.0108
0.85	7	0.267	0.0391	0.102	0.0184	2	0.195	0.0314	0.058	0.0109
0.9	∞	0.347	0.0453	0.100	0.0180	11	0.291	0.0413	0.051	0.0097

tive solution will emerge in this case than in the case with instantaneous redistribution of fish analyzed in Section 4. It was noted in Section 4 that N increases with c, a, and δ. Here we get $N = \infty$ for $c = 0.1$, $\delta = 0.9$, and $a = 0.2$. N falls quickly, however, when c or δ are reduced below these values; reducing δ to 0.85 (18% rate of discount) or c to 0.05 (lowest marginal cost of fish equal to 5% of the pristine stock) reduces N to 7 and 11, respectively. Even with this highly restricted migration, a cooperative solution is not guaranteed.[7]

Table I also shows figures that indicate the waste associated with agents choosing the individually optimal rather than the globally optimal solution (note that the pristine stock and its density are equal to 1). Superscript "o" refers to the global optimum while "*" refers to the individual optimum; if the number of participants were to increase by one the equilibrium solution would go from the global optimum to one very close to the individual optimum for the number of agents shown in the table. The individually optimal stock level is in all cases very much lower than the globally optimal level and in fact not much greater than the abandonment level with free access (c). The amount harvested is equal to the difference $G - S$. In the two cases shown in Table I the amount harvested in the noncooperative solution (the individual optimum) is only a quarter to one-half of the cooperative (globally optimal) harvest.

6. STRADDLING STOCKS

The final case we shall consider is one where a single agent has a high degree of control over a stock which is partly accessible to an indefinite number of agents. The case we have in mind is the one where a fish stock is largely contained within the 200-mile zone but straddles into the high seas. There are many real world cases of this kind, e.g., the groundfish stocks of the Grand Banks of Newfoundland, the Alaska pollack which is shared between the United States and Russia and straddles an area popularly known as the Donut Hole, and the Arcto-Norwegian cod which is shared by Norway and Russia and straddles an area similarly known as the Loophole.

[7] If the other players discover the defection immediately and start their punishment strategy in the same period as the defection occurs, their stock abandonment level in the period of defection will be the same as the defector's. The first term on the right-hand side of (21) will be divided by N, the second drops out and the last term will be multiplied by δ instead of δ^2. Expression (21) becomes a variation around an optimal path and is always negative. Hence defection will never be profitable and the cooperative equilibrium will be compatible with any number of agents.

We shall model this in a manner similar to the previous section. A certain fraction of the stock is supposed to be located within the "dominant agent's" area and the remainder outside and accessible to an indefinite number of agents. We ignore transboundary migration during the phase of exploitation; the dominant agent can choose the abandonment level of the stock within his area, while the remaining agents are assumed not to be interested in a cooperative solution, their number being indefinite, and hence choose an abandonment level for the remainder of the stock equal to the break-even marginal cost of fish ($p = c/S^*$). The transboundary externality is captured by letting the growth of the stock depend on total abandonment in the two areas, like in Eq. (18) above.

The dominant agent is assumed to choose an optimal abandonment level for his part of the stock, taking into account that the "fringe" agents choose the abandonment level $S^* = c/p$ for "their" part of the stock. The optimal steady-state abandonment level of the stock for the dominant agent will be given by a modified version of Eq. (20). With α being the share of the stock controlled by the dominant agent, and letting S and S^* denote the abandonment level of the dominant agent and the fringe agents, respectively, the objective function of the dominant agent becomes

$$V = \sum_{t=0}^{\infty} \delta^t \alpha \{ p[G(\alpha S_{t-1} + (1-\alpha)S^*) - S_t] - c[\ln G(\alpha S_{t-1} + (1-\alpha)S^*) - \ln S_t]\}, \qquad (19')$$

with the optimum abandonment level being given by

$$-(p - c/S^0) + \delta\alpha G'(\alpha S^0 + (1-\alpha)S^*)[p - c/G(\alpha S^0 + (1-\alpha)S^*)] = 0. \qquad (20')$$

A set of optimum solutions for the dominant agent are shown in Table II. The solution for $\alpha = 1$ is, of course, identical to the globally optimal solution. A striking feature of the solutions shown in Table II is how quickly the total present value and the optimum abandonment level of the stock fall with the dominant agent's share of the total stock. A dominant agent who controls 95% of the stock chooses an optimum stock level which is only 75% of the globally optimal level, and the total present value of profits (fringe plus dominant agent) is only 67% of the global optimum. This indicates that only a minor straddling of fish stocks into

TABLE II

Optimum Stock Level, Growth, and Present Value (PV) of Profits for Different Stock Shares of the Dominant Agent ($a = 0.2$, $c = 0.1$, and $\delta = 0.9$)

α	S^0 (dominant agent)	G	PV dominant agent	PV fringe	Sum PV
1	0.347	0.392	0.330	0	0.330
0.95	0.260	0.291	0.179	0.042	0.221
0.9	0.198	0.219	0.097	0.040	0.138
0.8	0.144	0.158	0.039	0.025	0.064
0.5	0.111	0.125	0.010	0.013	0.023
0.1	0.102	0.118	0.001	0.01	0.015

the high seas may result in substantial losses of efficiency. As the dominant agent's share of the stock is reduced further, the optimum abandonment level of the stock falls rapidly and so does the present value of aggregate profits; when the dominant agent controls one-half of the stock, the optimum abandonment level is only slightly above the free access abandonment level (0.1), and the aggregate profits are only about 5% of the global maximum.

Another interesting feature of the results in Table II is that beyond a certain point the fringe is not better off by having access to a larger part of the stock; the fringe's profit actually decreases slightly as its share of the stock increases from 5 to 10%. The reason is that the dominant agent maintains a large and productive stock as long as he has a high degree of control and some of the benefits of a large stock spills over to the fringe due to the growth externality.

7. CONCLUSION

The above analysis indicates that the number of agents that will cooperate in setting the exploitation rate for a shared fish stock is quite limited, but probably not much lower than the number of countries typically sharing a fish stock contained within 200 miles, and quite possibly higher. Cost heterogeneity will greatly limit this number, but in repeated games with an indefinite horizon low cost agents will not necessarily outfish high cost agents as in Clark's closed loop differential game [1]. The number of agents compatible with a self-enforcing cooperative solution is highly sensitive to the discount rate.

For stocks that are contained within separate national fishing zones but the growth of which is interrelated, depending on the aggregate stock size, the number of agents compatible with a self-enforcing cooperative equilibrium is much higher, but becomes very sensitive to fishing costs and the discount rate as these fall below a certain value. It is not at all unlikely that this critical number of agents will be comparable with or higher than the number of countries sharing stocks that are fully contained within 200 miles. Letting one of these zones represent the high seas with an indefinite number of agents, with one agent acting as a "leader" in the remaining zone, it appears, however, that even an ostensibly insignificant "fringe" may lead to significant losses of efficiency.

REFERENCES

1. C. W. Clark, Restricted access to common-property fishery resources: A game−theoretic analysis, *in* "Dynamic Optimization and Mathematical Economics" (P.-T. Liu, Ed.), pp. 117−132, Plenum, New York (1980).
2. R. D. Fischer and L. J. Mirman, Strategic dynamic interaction. Fish wars. *J. Econom. Dynamics Control* **16**, 267−287 (1992).
3. R. D. Fischer and L. J. Mirman, The compleat fish wars: Biological and dynamic interactions, *J. Environ. Econom. Management* **30**, 34−42 (1996).
4. D. Fudenberg and J. Tirole, "Game Theory," MIT Press, Cambridge, MA (1991).
5. R. Gibbons, "A Primer in Game Theory," Harvester Wheatsheaf, London (1992).
6. R. P. Hämäläinen, V. Kaitala, and A. Haurie, Bargaining on whales: A differential game model with Pareto optimal equilibria, *Oper. Res. Lett.* **3**, 5−11 (1984).
7. R. Hannesson, "Bioeconomic Analysis of Fisheries," Fishing News Books, Oxford (1993).

8. R. Hannesson, Sequential fishing: Cooperative and non-cooperative equilibria, *Natural Resource Modeling* **9**, 51–59 (1995).
9. D. Levhari and L. J. Mirman, The great fish war: An example using a dynamic Cournot–Nash solution, *Bell J. Econom.* **11**, 322–334 (1980).
10. M. Mesterton-Gibbons, Game–theoretic resource modeling, *Natural Resource Modeling* **7**, 93–147 (1993).
11. G. R. Munro, The optimal management of transboundary renewable resources, *Canad. J. Econom.* **12**, 355–376 (1979).
12. M. J. Osborne and A. Rubinstein, ‘‘A Course in Game Theory,’’ MIT Press, Cambridge, MA (1994).
13. J. Vislie, On the optimal management of transboundary renewable resources: A comment on Munro's paper, *Canad. J. Econom.* **2**, 870–875 (1987).