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Fish Wars on the High Seas: Erecting Economic Barriers to Entry

by

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Abstract

The 1993 U.N. Straddling Stock Agreement prescribes a multi-national organizational structure for management of an exploited marine fish stock, one whose range straddles both "Extended Economic Zones" (EEZs) and high seas waters. However, the Agreement provides to the Regional Organization no coercive enforcement powers. In this connections two problems in particular have been cited: The first, called the "interloper problem", concerns the difficulty of controlling the harvesting by non-member vessels. The second problem, called the "new-member problem", concerns the inherent difficulties of negotiating mutually acceptable terms of entry.

Here we explore the extent to which the coalition, by exerting economic power alone, might be able attain effective leverage in these management-control controversies. Specifically, we will examine whether the coalition might successfully employ traditional monopolistic "entry barriers".

Game-theoretic economic analysis provides some helpful insights into this question, but the open-access character of resource exploitation on the high seas complicates its applicability here. On the other hand, the game is asymmetric, with the incumbent coalition enjoying certain advantages.

Our analysis lends support to the thesis that usually leverage to enforce regional management control must be sought elsewhere, other than through direct application of economic power within the harvesting sector.

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INTRODUCTION[1]

The 1993 U.N. Straddling Stock Agreement prescribes a multi-national organizational structure for the management of exploited high seas "straddling" fish stocks—those whose range is partly in international waters, but which typically overlaps certain coastal states' Extended Economic Zones. The Agreement specifies that harvesting, wherever within the biological range it occurs, should be coordinated by a coalition of the traditional harvesting states, acting through a U.N. sanctioned Regional Fisheries Management Organization. While simultaneously recognizing the right of *all* states to utilize the biological resources of the high seas, the agreement calls for those nations who wish to participate in harvest of the straddling stock, but are not currently members of the Regional Organization, to declare a willingness to join and to enter into negotiations over mutually acceptable terms of entry.

However, the agreement provides to the Regional Organization no coercive enforcement powers, to exclude non-member harvest or set the terms of entry into membership. This lack of enforcement power has caused many to doubt the effectiveness of the proposed regional management mechanism. Two problems in particular have been cited:

The first, called by Gordon Munro (1999) the "interloper problem", concerns the difficulty of controlling the harvesting by non-member vessels, including individually operated vessels (perhaps flying flags-of-convenience) but also including coordinated multi-vessel "distant water fleets" seeking targets-of-opportunity, intent on skimming off a bountiful harvest wherever it occurs, but with little interest in the long-term conservation of the stocks.

The second problem identified by Munro, the "new member problem", concerns the

[1]FINANCIAL SUPPORT FROM THE US NATIONAL SCIENCE FOUNDATION IS ACKNOWLEDGED.

inherent difficulties of negotiating, in a timely manner, mutually acceptable terms of entry, which will specify the petitioning nation's membership rights and obligations. Indeed the interests of the current members and the applicant are often strongly opposed, with current members facing the likelihood of having to give up a portion of their present quotas to the newcomer, and the applicant believing that it might be better off staying outside of the coalition, continuing to harvest profitably while facing fewer constraints.

In this article we shall explore the extent to which the coalition of states in the Regional Organization might, by exerting economic power alone, be able to attain effective leverage in these management-control contests so as to bring them to satisfactory resolution. Specifically, we wish to examine whether the coalition might successfully employ traditional monopolistic "entry barriers", to limit non-member harvesting and achieve effective management control of the fishery.

The existing game-theoretic analysis of industrial organization, (e.g. Tirole, 1988), provides some helpful insights into this question, but its applicability here is complicated by the open-access character of resource exploitation in a high seas fishery. This derives from the fact that all harvesters are exploiting a common biological stock pool. As we shall see, this circumstance reduces the effectiveness of potential economic barriers, and introduces elements of the "tragedy of the common" into the competitive game between the regional coalition and a non-member harvester.

In this article we briefly describe a series of models, with which we attempt to capture several strategically important aspects of the competition. Detailed analysis of these models will appear elsewhere.

The harvesting competition is essentially dynamic, reflecting trade-offs between present and future returns. It is only when we incorporate explicit dynamic features of the evolving high seas fishery that the more subtle strategic nuances of the competition can fully emerge. In this article we outline the implications of several of these dynamic models that we have been studying.

DYNAMIC MONOPOLISTIC OPERATION: ACCOMMODATING A COMPETITIVE FRINGE

In the simplest dynamic fisheries model, the *surplus production model*, the state of a fish population is described through a single statistic, namely its ***biomass***. At the beginning of the harvesting season the biomass is termed the *recruitment*, which will be denoted by R. The biomass at the end of the season is called *escapement*, and will be denoted by S. Thus the ***harvested biomass*** H is

$$H = R - S.$$

Biomass grows between successive harvest seasons, with the escapement S at the end of a particular season determining recruitment R^+ at the beginning of the next harvesting season. That dependence is quantified in a so-called ***stock-recruitment relation***

$$R^+ = F(S).$$

Here, for simplicity, we will assume that $F(S)$ is an increasing concave function, that an unharvested stock will attain a steady-state when it has reached its *carrying-capacity* K, at which.

$$F(K) = K,$$

and that $F(0) = 0$. Schematically, the stock level is thus seen to evolve seasonally according to

$$R \to S \to F(S) = R^+.$$

During the harvesting season, the stock will be drawn down gradually, from initial R to final S, with the net return per-unit of landings depending on current stock level

x within-season, and given by

$$\pi(x) = p - C(x).$$

Here p is a fixed unit price for the landed harvest and $C(x)$ is the unit cost of harvesting when the stock level is x. This unit cost is assumed to increase, as the stock level is drawn down in the course of the season. Typically

$$C(x) = c/x.$$

In this case, the bionomic break-even harvesting stock level is

$$S^o = \frac{c}{p}.$$

The net cumulative return $\widehat{\Pi}$ from the entire season's harvest is thus

$$\widehat{\Pi}(R, S) = \int_S^R \pi(x)dx = pH - \int_S^R C(x)dx.$$

If the stock is harvested by the regional consortium operating as a monopoly, it is typically managed to maximize the discounted sum of these annual returns, over an infinite time horizon:

$$V(R_0) = \max_{\{S_t\}} \sum_{t=0}^{\infty} \gamma^t \cdot \widehat{\Pi}(R_t, S_t), \text{where } R_{t+1} = F(S_t).$$

To achieve this, standard analysis requires determining an optimal *target escapement level,* S^*, which is independent of t, and adopting a policy of always harvesting-down to this level whenever recruitment is above it. When recruitment is below the target, there should be no harvest, allowing the stock to grow. Thus optimally:

$$S_t = \min[R_t, S^*].$$

The optimal S^* satisfies the relation

$$\pi(S^*) = \gamma F'(S^*) \cdot \pi[F(S^*)].$$

This is a "marginal rule", and it asserts that the target level is to be chosen so that the marginal value of the final unit harvested equals that it would have been if instead it were left unharvested (in order to contribute to the following year's recruitment). Consistently targeting to achieve this escapement will maximize the discounted sum of net harvest returns.

Now suppose that a small second fleet enters the fishery, and engages in harvesting at constant effort throughout the season. Suppose also that the invader's harvest is confined to the international zone, and occurs early in the season, prior to any harvest by the incumbent coalition. We shall assume (for now) that the regional coalition, fishes only in the member-states' EEZs, and ask for its optimal response to the invasion.

As in our previous static model an *aggressive* competitive response of the incumbent coalition would be to fish-down the stock preemptively, thereby making harvesting less profitable for a potential invader. But this strategy also makes harvesting less profitable for the incumbent fleet, even (as we shall see later) when the preemptive harvest is confined to international waters and compensated for within the EEZs.

It thus should be clear that such an aggressive strategy by the incumbent fleet is particularly inappropriate when the invading fleet is small, constituting only a minor competitive fringe to a much larger establishment fleet. Overharvesting to avoiding the relatively small cost resulting from the presence of the fringe vessels imposes incurring a much larger self-inflicted harvesting cost to the incumbent fleet itself.

By contrast, let us examine the optimal strategy for the incumbent fleet, if it elects to *coexist* with a small competitive fringe in the fishery. For simplicity, assume that the harvest occurs sequentially, with the fringe fleet's harvest taking place *prior* to the entry of the incumbent fleet.

In this case, the *effective* stock-recruitment relation observed by the home fleet becomes

$$\widehat{R}^{+} = G(S) = \xi F(S),$$

with $\xi < 1$, where $\widehat{R}^{+}$ is the portion of the recruitment which remains following the fringe harvest. Substituting G for F in the above monopolistic policy equations easily shows that, while the incumbent fleet will cut back its harvest level, nevertheless the total harvest by the two fleets will be larger than the monopolist's optimal level. In particular, the optimal competitive escapement $\widehat{S}^{\#}$ will be lower than the monopolist's optimal escapement:

$$\widehat{S}^{\#} < S^{*}.$$

Thus unit harvesting costs will be higher, so that net return per unit of harvest will be lower.

Actually, the impact on the stock likely will be even greater than this analysis indicates. This is because (taking account of "sunk costs" in fleet harvesting capacity), the incumbent fleet will not immediately cut back its effort level, but will continue to fully utilize its total fleet capacity, which will deteriorate only slowly.

These results are not surprising: they merely corroborate the general expectation of inefficiency of competing harvests of a common pool resource. However the analysis underlines the important fact that any activity which significantly decreases fish stock levels will decrease individual harvesting efficiency of *all* vessels, friend and foe alike. Thus normally the cumulative cost to a large incumbent fleet will greatly exceed that to a small fringe invader.

This outcome depends very much on assuming that the two fleets meet on a "level playing field". But in fact the competition normally will not be a contest between equals. There are usually circumstances present which favor the incumbent. We turn next to an examination of several of these situations, where the incumbent fleet may be able to exploit asymmetries in the harvesting game, and turn them to advantage.

DISTANT-WATER FLEETS AND PULSED HARVESTING

Prior to the introduction of the national Extended Economic Zones, powerful distant-water fishing fleets (DWFs) roamed the coastal seas, seeking targets of opportunity. Typically these fleets practiced pulse harvesting, heavily fishing-down an abundant stock along a particular shore, and then moving on to harvest elsewhere waiting for the depleted stock to recover before returning to exploit it again. Thus their exploitation pattern in any given fishery would tend to be of a periodic pulsing nature, rather than a steady annual harvesting.

With the establishment of the EEZs worldwide, it was expected that these wide-ranging fleets would simply be replaced by the expanding national fleets of the coastal states. Instead the older vessels often were not decommissioned, and the result has been massive excessive harvesting capacity worldwide. In this circumstance it is entirely natural that distant-water fleets, being excluded from the extended coastal economic zones, would now concentrate their harvest effort on the high-seas portions of straddling stock ranges. This indeed has come about, and stocks in many such areas have been severely depleted.

An example is provided by the rich groundfish stocks in the Bering Sea, formerly harvested mainly by the US, Russia, and Japan. Creation of the US. and Russian EEZs also created the "Doughnut Hole", a high seas portion of the range which is entirely surrounded by nationally-managed waters. The Japanese fleet, now banished from the EEZs, has concentrated on the Doughnut Hole, and in a few years badly depleted the stock there. There is now little interest in further fishing in the Hole, but restraint by the US. and Russian fleets can be expected to rebuild the stocks. Thus this fishery too might expect to become a target for a pulse-fishing distant water fleet. A natural preemptive strategy on the part of Russia and the United States would be to set up a Regional Management Organization, to control third-party harvesting in the Doughnut Hole.

Another example is the important Southern Bluefin Tuna fishery, partly in Australia's EEZ and partly on the high seas, where the stock traditionally has been exploited by Japan and to a lesser degree by New Zealand. At this time the stock is not believed to be severely over-harvested. However recently other countries have begun high seas harvesting, notably Indonesia, South Korea, Taiwan, and even the EU, increasing the likelihood that uncoordinated future harvesting might lead to stock degradation. Thus one might expect that Australia, Japan, and perhaps New Zealand might initiate efforts to establish a joint management regime which, in accord with the straddling stock agreement, then would regulate the entire Southern Bluefin range.

Once a Regional Management Organization has been established, the original members naturally would prefer to exclude harvesting by any others. However, in the absence of coercive controls, one can predict that high seas harvesting by non-member-states eventually will become again a problem. As depleted stocks are rebuilt, national fleets of outsider states may well be tempted to return to exploit the open access fishery on the high seas portion of the range.

Such a non-member state may very likely express an interest in joining the regional grouping. However it will wish to enter on favorable terms–terms that necessarily will adversely affect the harvest quotas already assigned to current members . Thus a natural strategy for the applicant will be to continue its independent harvesting while it negotiates a stance which will ensure it immediately profit while simultaneously enhancing its bargaining position over the ultimate terms of its entry.

We shall undertake to model the strategic aspects of such a confrontation. We begin, however, by reviewing and expanding on analysis of a model by William Reed (1974)–see also the related model by Jaquette (1974)–which can be applied to explain the earlier pulse fishing by distant-water-fleets, prior to the creation of coastal states'

Extended Economic Zones.

Monopolistic harvesting

Here we review the characteristics of the two fleets, and briefly describe the *modus operandi* of each when it harvests monopolistically. Their respective bionomic stock levels are defined as

$$S^o_\alpha = c_\alpha/p \quad \text{and} \quad S^o_\beta = c_\beta/p.$$

Neither fleet will harvest when the stock level is below its break-even level.

The distant-water fleet's seasonal harvest return function Π_α includes a fixed cost of entry κ:

$$\Pi_\alpha = H[R_\alpha(t) - S_\alpha(t)] \cdot \left\{ \int_{S_\alpha}^{R_\alpha} \pi_\alpha dS - \kappa \right\},$$

with

$$H[R - S] = \begin{cases} 1 \text{ if } S < R \\ 0 \text{ if } S = R, \end{cases} .$$

while that of the incumbent fleet does not:

$$\Pi_\beta = \int_{S_\beta}^{R_\beta} \pi_\beta dS.$$

Here, for $\nu = \alpha$ or β, $\pi_\nu(S)$ is monotone decreasing, with $\pi_\nu(S^o_\nu) = 0$ at S^o_ν, the bionomic stock level, where by assumption $0 < S^o_\nu < K$.

For each fleet, the long-term objective is to maximize the discounted sum of net annual returns. Respectively[2],

$$U_\alpha[R_\alpha(0)] = \sum_{t=0}^{\infty} \gamma^t H[R_\alpha(t) - S_\alpha(t)] \cdot \left\{ \int_{S_\alpha(t)}^{R_\alpha(t)} \pi_\alpha - \kappa \right\}$$

[2] Henceforth the dS-notation in the integrals is skipped to improve the appearance. That is, $\int \pi dS \to \int \pi$.

with

$$R_\alpha(t+1) = F[S_\alpha(t)]$$

and

$$U_\beta[R_\beta(0)] = \sum_{t=0}^{\infty} \gamma^t \int_{S_\beta(t)}^{R_\beta(t)} \pi_\beta.$$

Consider now the characteristics of an optimal harvest policy for one or the other of these fleets, when it is able to operate as an unopposed monopolist in a seasonal single-stock fishery.

If the β-fleet operates as an unopposed monopolist, so that stock-dynamics follow the pattern

$$R_\beta \to S_\beta \to R_\beta^+ = F(S_\beta),$$

then the *optimal* β-harvest policy is known to be a policy of *most-rapid approach to a target escapement* S_β^*. That is, in a season when β-recruitment is R_β,

$$S_\beta = \min[S_\beta^*, R_\beta].$$

It is well-known that the optimal target escapement satisfies the marginal rule (the so-called "golden rule").

$$\gamma F'(S_\beta^*) = \pi_\beta[S_\beta^*]/\pi_\beta[F(S_\beta^*)].$$

We assume that the solution S_β^* of this equation satisfies $S_\beta^0 < S_\beta^* < K$, so that the β -fleet can indeed harvest profitably as a monopoly.

For the distant-water α-fleet, harvesting as an unopposed monopolist, a somewhat more complicated harvesting policy is appropriate. Indeed, the α-fleet will not enter in any given season unless the resulting long-run enhancement of payoff, that would result from that entry, would exceed the added fixed-cost which would thereby be incurred.

It was shown independently by Reed [1972] and Jaquette [1972] that the optimal policy for the *monopolistic α-fleet* is a so-called $(\widehat{S}_\alpha, \widehat{R}_\alpha)$*-policy*, which specifies both a *target escapement* $\widehat{S}_\alpha \geq S^o_\alpha$ and *harvest threshold* $\widehat{R}_\alpha \geq \widehat{S}_\alpha$. Such a policy requires, for given recruitment R_α, that

$$S_\alpha = \mathbb{S}_\alpha(R_\alpha; \widehat{S}_\alpha, \widehat{R}_\alpha) = \begin{cases} \widehat{S}_\alpha, & \text{if } \widehat{R}_\alpha \leq R_\alpha \\ R_\alpha, & \text{if } R_\alpha \leq \widehat{R}_\alpha. \end{cases}$$

Note that we have specified the equality of these two expressions for U_α at $R = \widehat{R}_\alpha$. That is, the threshold recruitment level $\widehat{R}_\alpha$ has been chosen so that at that level the α-fleet will be indifferent between entering or not entering.

Once again, we specify that

$$0 < S^o_\alpha < \widehat{S}_\alpha \leq \widehat{R}_\alpha < K,$$

which, for the assumed characteristics of the stock recruitment relation $F(S)$, will assure that the α-fleet can harvest profitably (in a periodic pulsed fashion) as a monopolist.

Indeed, let $F^{[n]}(S)$ denote the n-fold composition of the transformation F with itself, i.e.

$$F^{[0]}(S) = S; \quad F^{[1]}(S) = F(S); \quad F^{[2]}(S) = F \circ F(S) = F(F(S)); \quad \text{etc.}$$

Since F is monotone and concave, with a single fixed-point at K therefore, for $0 < S < K$,

$$F^{[n]}(S) < F^{[n+1]}(S)$$

and

$$\lim_{n \to \infty} F^{[n]}(S) = K$$

It follows that there is a unique integer $N \geq 0$ such that

$$F^{[N-1]}(\widehat{S}_\alpha) < \widehat{R}_\alpha \leq F^{[N]}(\widehat{S}_\alpha).$$

Furthermore, *as we shall show*, under monopolistic harvest by the α-fleet, the dynamic trajectory of the fish stock, from any initial recruitment R_α, will lead to a cyclic steady-state pattern of harvest, of period N. For example, for $N = 3$ and $R_\alpha > \widehat{R}_\alpha$, the initial transient and subsequent steady-state pattern of recruitments and subsequent escapements is illustrated in Figure 1. We shall refer to the integer N as the *periodicity of the given* $(\widehat{S}_\alpha, \widehat{R}_\alpha)$*-policy*.

Given the fact of periodicity, it is easy to determine the optimal $(\widehat{S}_\alpha, \widehat{R}_\alpha)$-policy for the fleet. Iterating the steady-state pattern, it follows that

$$U_\alpha[F^{[N]}(\widehat{S}_\alpha)] = \frac{1}{1-\gamma^N}\left\{\int_{\widehat{S}_\alpha}^{F^{[N]}(\widehat{S}_\alpha)} \pi_\alpha - \kappa\right\}$$

Furthermore, for any $R_\alpha > \widehat{R}_\alpha$, one has

$$U_\alpha[R_\alpha] = \int_{F^{[N]}(\widehat{S}_\alpha)}^{R_\alpha} \pi_\alpha + U_\alpha[F^{[N]}(\widehat{S}_\alpha)] = \int_{F^{[N]}(\widehat{S}_\alpha)}^{R_\alpha} \pi_\alpha + \frac{1}{1-\gamma^N}\left\{\int_{\widehat{S}_\alpha}^{F^{[N]}(\widehat{S}_\alpha)} \pi_\alpha - \kappa\right\}.$$

Making explicit the dependence of U_α upon $\widehat{S}_\alpha$, we may compute that

$$\partial_{\widehat{S}_\alpha} U_\alpha(R_\alpha, \widehat{S}_\alpha) = \frac{1}{1-\gamma^N}\left\{\gamma^N \frac{d}{d\widehat{S}_\alpha} F^{[N]}(\widehat{S}_\alpha) \cdot \pi_\alpha[F^{[N]}(\widehat{S}_\alpha)] - \pi_\alpha(\widehat{S}_\alpha)\right\}.$$

Optimization occurs where

$$\partial_{\widehat{S}_\alpha} U_\alpha(R_\alpha, \widehat{S}_\alpha) = 0,$$

and hence $\widehat{S}_\alpha = S_\alpha^{*N}$, as defined through the formula

$$\gamma^N \frac{d}{d\widehat{S}_\alpha} F^{[N]}(S_\alpha^{*N}) = \frac{\pi_\alpha(S_\alpha^{*N})}{\pi_\alpha[F^{[N]}(S_\alpha^{*N})]}$$

This is simply the golden rule for a pulsing harvest of period N: the N-period stock-recruitment relation is $F^{[N]}(\widehat{S}_\alpha)$ and the N-period discount factor is γ^N

It remains to compute the threshold recruitment $\widehat{R}_\alpha$,which we are assuming lies on the interval

$$F^{[N-1]}(S_\alpha^{*N}) < \widehat{R}_\alpha \leq F^{[N]}(S_\alpha^{*N}).$$

As noted above, $\widehat{R}_\alpha$ is characterized by the requirement of continuity of the utility function $U_\alpha(R_\alpha)$ there. Using this condition, and the above explicit expressions for utility at $R_\alpha = F(\widehat{R}_\alpha)$ and at $F(\widehat{S}_\alpha)$, we have that

$$\begin{aligned} \kappa &= \int_{\widehat{S}_\alpha}^{\hat{R}_\alpha} \pi_\alpha + \gamma \left\{ U_\alpha[F(\widehat{S}_\alpha)] - U_\alpha[F(\widehat{R}_\alpha)] \right\} = \\ &= \frac{1-\gamma^N}{1-\gamma} \left[\int_{S*N}^{R*N} \pi_\alpha - \gamma \int_{S*N}^{F[R*N]} \pi_\alpha \right] + \gamma^N \int_{S*N}^{F^{[N]}(S*N)} \pi_\alpha . \end{aligned}$$

Competitive Harvest

We assume that, in the competitive setting, the incumbent fleet continues to choose a most-rapid-approach policy, targeting an appropriate escapement $\widehat{S}_\beta$, where

$$0 < S_\beta^o \leq \widehat{S}_\beta < K.$$

Hence the α-fleet will "see" an *effective stock-recruitment relation* $S_\alpha \rightarrow R_\alpha^+ = G_\alpha[S_\alpha]$:

$$R_\alpha^+ = G_\alpha[S_\alpha] \triangleq F[\mathbb{S}_\beta(S_\alpha; \widehat{S}_\beta)] = F[\min(S_\alpha; \widehat{S}_\beta)] = \min[F(S_\alpha), F(\widehat{S}_\beta)].$$

More generally, across n periods

$$G_\alpha^{[n]}(S_\alpha) = \min[F^{[n]}(S_\alpha), F(\widehat{S}_\beta)].$$

We shall also assume that, *even in the presence of an incumbent competitor*, the α-fleet will choose an $(\widehat{S}_\alpha, \widehat{R}_\alpha)$-policy, with appropriate target and threshold and such that

$$0 < S_\alpha^o \leq \widehat{S}_\alpha \leq \widehat{R}_\alpha < K.$$

As noted before, for any such α-policy there is a unique $N \geq 0$ such that

$$\widehat{S}_\alpha \leq F^{[N-1]}(\widehat{S}_\alpha) < \widehat{R}_\alpha \leq F^{[N]}(\widehat{S}_\alpha).$$

In the presence of the competing α-fleet, the incumbent β-fleet faces the *effective stock-recruitment relation* $S_\beta \longrightarrow R_\beta^+ = G_\beta[S_\beta]$:

$$R_\beta^+ = G_\beta(S_\beta) \triangleq \mathbb{S}_\alpha[F(S_\beta), \widehat{S}_\alpha, \widehat{R}_\alpha] \triangleq \begin{cases} \widehat{S}_\alpha & \text{if } \widehat{R}_\alpha \leq F(S_\beta), \\ F(S_\beta) & \text{if } F(S_\beta) \leq \widehat{R}_\alpha. \end{cases}$$

Here explicit notation of the dependence of G_β on $(\widehat{S}_\alpha, \widehat{R}_\alpha)$ has been suppressed.

We turn now to an analysis of how the relative strengths of the fleets will condition the outcome of their competition. Specifically we must characterize the Nash equilibrium policy profile (or profiles), of the form

$$\{[\widehat{S}_\alpha, \widehat{R}_\alpha], \widehat{S}_\beta\},$$

that are consistent with the circumstances of the long-run competition, and that would determine the consequent dynamics of the fishery. As it turns out, the outcome depends primarily on the size of $F(\widehat{S}_\beta)$ relative to the interval $[\widehat{R}_\alpha, F^{[N]}(\widehat{S}_\alpha)]$: We shall see that, after an initial transient period, then

if $\widehat{R}_\alpha \leq F^{[N]}(\widehat{S}_\alpha) \leq F(\widehat{S}_\beta)$ then the β-fleet will be excluded from the fishery;
if $\widehat{R}_\alpha \leq F(\widehat{S}_\beta) < F^{[N]}(\widehat{S}_\alpha)$, then the fleets will coexist in the fishery;
and if $F(\widehat{S}_\beta) < \widehat{R}_\alpha \leq F^{[N]}(\widehat{S}_\alpha)$, then the α-fleet will be excluded.

We shall examine each case in turn.

α-Fleet Dominance: $F^{[N-1]}(\widehat{S}_\alpha) < \widehat{R}_\alpha \leq F^{[N]}(\widehat{S}_\alpha) \leq F(S_\beta^0)$.—
Assuming that

$$\widehat{S}_\alpha \leq F^{[N-1]}(\widehat{S}_\alpha) < \widehat{R}_\alpha \leq F^{[N]}(\widehat{S}_\alpha) \leq F(\widehat{S}_\beta)$$

Then also

$$\widehat{S}_\alpha < F^{[-1]}(\widehat{R}_\alpha) \leq \widehat{S}_\beta.$$

Hence, following a brief transient period, a steady-state pattern will develop, with only the α-fleet harvesting and a period N repeated pattern of recruitments and subsequent escapements. The case for $N = 3$ is illustrated in Figure 2.

Iterating this steady-state pattern, it follows (as for an *unopposed* α-fleet monopoly) that for any $R_\alpha > \widehat{R}_\alpha$

$$U_\alpha[R_\alpha] = \int_{F^{[N]}(\hat{S}_\alpha)}^{R_\alpha} \pi_\alpha + \frac{1}{1-\gamma^N} \left\{ \int_{\hat{S}_\alpha}^{F^{[N]}(\hat{S}_\alpha)} \pi_\alpha - \kappa \right\}$$

As in that case, the optimal choice of target escapement may be found by differentiating this expression partially with respect to $\widehat{S}_\alpha$. However in a competitive harvest, because of the expected reaction of the competing β-fleet, there is an additional restriction on the feasible set of values of $\widehat{S}_\alpha$, namely that

$$F^{[N-1]}(\widehat{S}_\alpha) \leq \widehat{S}_\beta.$$

Thus optimally

$$\widehat{S}_\alpha = \min[S_\alpha^{*N}, F^{[1-N]}(\widehat{S}_\beta)],$$

where S_α^{*N} is, as before, the target escapement for the unopposed monopoly.

On the other hand, note that a payoff to the β-fleet, under the present scenario, can occur only within an initial time interval, during which $R_\alpha > \widehat{S}_\beta$. Thus

$$U(R_\alpha, \widehat{S}_\beta) = \int_{\widehat{S}_\beta}^{R_\alpha} \pi_\beta.$$

This payoff is optimized, under the assumed constraint that

$$\widehat{R}_\alpha \leq F(\widehat{S}_\beta),$$

by making $\widehat{S}_\beta$ as small as possible. Hence

$$\widehat{S}_\beta = S_\beta^{\infty}.$$

Finally, the choice of the policy $(\widehat{S}_\alpha, \widehat{R}_\alpha)$ determines the corresponding fixed cost κ. Recall that the threshold recruitment level $\widehat{R}_\alpha$ has been chosen so that at that level the α-fleet will be indifferent between entering or not entering. Hence

$$\int_{\widehat{S}_\alpha}^{\widehat{R}_\alpha} \pi_\alpha - \kappa + \gamma U_\alpha[F(\widehat{S}_\alpha)] = U_\alpha[F(\widehat{R}_\alpha)]$$

and so

$$\kappa = \frac{1-\gamma^N}{1-\gamma}\left[\int_{\widehat{S}_\alpha}^{\widehat{R}_\alpha} \pi_\alpha - \gamma \int_{\widehat{S}_\alpha}^{F[\widehat{R}_\alpha]} \pi_\alpha\right] + \gamma^N \int_{\widehat{S}_\alpha}^{F^{[N]}(\widehat{S}_\alpha)} \pi_\alpha.$$

Note that, for fixed N and $\widehat{S}_\alpha$, this expresses κ as a monotone increasing function of $\widehat{R}_\alpha$ on its interval of validity

$$F^{[N-1]}(\widehat{S}_\alpha) < \widehat{R}_\alpha \leq F^{[N]}(\widehat{S}_\alpha).$$

As a special case, the policy profile

$$\{[S_\alpha^{*N}(\kappa), R_\alpha^{*N}(\kappa)], S_\beta^o\},$$

where

$$F^{[N-1]}(S_\alpha^{*N}) < R_\alpha^{*N}(\kappa) \leq F^{[N]}(S_\alpha^{*N}) \leq F(S_\beta^o),$$

constitutes a Nash equilibrium, with the β-fleet excluded, after an initial transient period, and the α-fleet operating monopolistically, entering periodically with an optimal pulsing harvest of period N.

Different N-cycles are possible for each κ, and it is not indifferent which one is chosen. As α is the one who produces the cycle, he can choose the one that is optimal for him. Typically this will be the cycle with lowest N.

Coexistence: $\widehat{R}_\alpha \leq F(\widehat{S}_\beta) < F^{[N]}(\widehat{S}_\alpha)$.—

If

$$\widehat{S}_\alpha \leq F^{[N-1]}(\widehat{S}_\alpha) < \widehat{R}_\alpha \leq F(\widehat{S}_\beta) < F^{[N]}(\widehat{S}_\alpha)$$

then also

$$F^{[N-2]}(\widehat{S}_\alpha) \leq F^{[-1]}(\widehat{R}_\alpha) \leq \widehat{S}_\beta < F^{[N-1]}(\widehat{S}_\alpha)$$

In particular,

$$\begin{aligned} \text{for } N &= 1, \quad \widehat{S}_\beta < \widehat{S}_\alpha < R_\alpha \leq F(\widehat{S}_\beta) < F(\widehat{S}_\alpha) \text{ and} \\ \text{for } N &> 1, \quad \widehat{S}_\alpha < \widehat{S}_\beta < F^{[N-1]}(\widehat{S}_\alpha) < \widehat{R}_\alpha \leq F(\widehat{S}_\beta) < F^{[N]}(\widehat{S}_\alpha). \end{aligned}$$

Coordinating on such a policy-profile will lead to an N-period steady-state in which both fleets participate in the harvest. The evolution for $N = 1$ is illustrated in Figure 3, and the evolution for $N = 4$ is illustrated in Figure 4.

For an arbitrary N,

$$U_\alpha[F(\widehat{S}_\beta)] = \frac{1}{1-\gamma^N} \int_{\widehat{S}_\alpha}^{F(\widehat{S}_\beta)} \pi_\alpha$$

and for $R_\alpha \geq \widehat{R}_\alpha$,

$$U_\alpha(R_\alpha) = \int_{F(\widehat{S}_\beta)}^{R_\alpha} \pi_\alpha + U_\alpha[F(\widehat{S}_\beta)] = \int_{F(\widehat{S}_\beta)}^{R_\alpha} \pi_\alpha + \frac{1}{1-\gamma^N} \int_{\widehat{S}_\alpha}^{F(\widehat{S}_\beta)} \pi_\alpha$$

Noting explicitly the dependence of U_α on the target escapement $\widehat{S}_\alpha$, and differentiating the last expression by this parameter, then

$$\partial_{\widehat{S}_\alpha} U_\alpha(R_\alpha; \widehat{S}_\alpha) = -\pi_\alpha(\widehat{S}_\alpha)/(1-\gamma^N).$$

We have

$$F(\widehat{S}_\beta) \geq \widehat{R}_\alpha > F^{[N-1]}(\widehat{S}_\alpha) > \widehat{S}_\beta \Rightarrow F^{(1-N)}(\widehat{S}_\beta) < \widehat{S}_\alpha \leq F^{(2-N)}(\widehat{S}_\beta).$$

Therefore the first order condition establishes an ϵ-optimal choice of $\widehat{S}_\alpha$ as

$$\widehat{S}_\alpha = \min\left\{F^{(2-N)}(\widehat{S}_\beta) - \epsilon, \max\left(S_\alpha^0, F^{(1-N)}(\widehat{S}_\beta)\right)\right\}$$

where $\epsilon = 0$ corresponds to exclusion of β.

Likewise,

$$U_\beta[F^{[N-1]}(\widehat{S}_\alpha)] = \frac{1}{1-\gamma^N}\int_{\widehat{S}_\beta}^{F^{[N-1]}(\widehat{S}_\alpha)} \pi_\beta$$

and for $R_\beta \geq \widehat{S}_\beta$,

$$U_\beta(R_\beta) = \int_{F^{[N-1]}(\widehat{S}_\alpha)}^{R_\beta} \pi_\beta + U_\beta[F^{[N-1]}(\widehat{S}_\alpha)] = \int_{F^{[N-1]}(\widehat{S}_\alpha)}^{R_\beta} \pi_\beta + \frac{1}{1-\gamma^N}\int_{\widehat{S}_\beta}^{F^{[N-1]}(\widehat{S}_\alpha)} \pi_\beta \,.$$

Then

$$\partial_{\widehat{S}_\beta} U_\beta(R_\beta, \widehat{S}_\beta) = -\pi_\beta(\widehat{S}_\beta)/(1-\gamma^N),$$

and, under the constraint that

$$\widehat{R}_\alpha \leq F(\widehat{S}_\beta) \;\text{ and }\; F^{(N-1)}(\widehat{S}_\alpha) \geq \widehat{S}_\beta$$

the optimal choice of $\widehat{S}_\beta$ is

$$\widehat{S}_\beta = \max[S^o_\beta, F^{[-1]}(\widehat{R}_\alpha)]$$

and $S^0_\beta \leq F^{(N-1)}(\widehat{S}_\alpha)$. It follows, in particular, that if

$$F^{[N-1]}(S^o_\alpha) < \widehat{R}^o_\alpha \leq F(S^o_\beta) \leq F^{[N]}(S^o_\alpha),$$

and if

$$\begin{aligned} \widehat{\kappa}^o \;&\triangleq\; \int_{\widehat{S}_\alpha}^{\widehat{R}_\alpha} \pi_\alpha + \gamma\left\{U_\alpha[F(\widehat{S}_\alpha)] - U_\alpha[F(\widehat{R}_\alpha)]\right\} = \\ &=\; \frac{1-\gamma^N}{1-\gamma}\left[\int_{S^o_\alpha}^{R^o_\alpha} \pi_\alpha - \gamma\int_{S^o_\alpha}^{F[R^o_\alpha]} \pi_\alpha\right] + \gamma^N \int_{S^o_\alpha}^{F^{[N]}(S^o_\alpha)} \pi_\alpha, \end{aligned}$$

then the policy profile $\{[S^o_\alpha, \widehat{R}^o_\alpha], S^o_\beta\}$ will provide the unique coexistent, period N Nash equilibrium of target/threshold type corresponding to the fixed cost $\widehat{\kappa}^o$.

β-Fleet Dominance: $F(\widehat{S}_\beta) < \widehat{R}_\alpha$.

When

$$F(\widehat{S}_\beta) < \widehat{R}_\alpha$$

and $\widehat{S}_\beta \geq S^0_\beta$ then, following an initial transient period, the α-fleet will be excluded, and the β-harvest will attain a steady-state with escapements $\widehat{S}_\beta$ (not necessarily at the monopolistic level) and subsequent recruitments $\widehat{R}_\beta = F(\widehat{S}_\beta)$.

In fact, the above inequality implies for an N-cycle that

$$\widehat{S}_\beta < F^{[N-1]}(\widehat{S}_\alpha);$$

Hence a typical pattern of escapements and subsequent recruitments for $N = 3$ and $F(\widehat{S}_\alpha) < \widehat{S}_\beta$ terminating in a steady-state single-period cycle which excludes the α-fleet is illustrated in Figure 5.

Clearly

$$U_\beta[F(\widehat{S}_\beta)] = \frac{1}{1-\gamma}\int_{\widehat{S}_\beta}^{F(\widehat{S}_\beta)} \pi_\beta,$$

and for $R_\beta > \widehat{S}_\beta$,

$$U_\beta[R_\beta] = \int_{\widehat{S}_\beta}^{R_\beta} \pi_\beta + \gamma U_\beta[F(\widehat{S}_\beta)] = \int_{\widehat{S}_\beta}^{R_\beta} \pi_\beta + \frac{\gamma}{1-\gamma}\int_{\widehat{S}_\beta}^{F(\widehat{S}_\beta)} \pi_\beta$$

Making explicit the dependence of U_β upon $\widehat{S}_\beta$, and differentiating the last expression partially by $\widehat{S}_\beta$,

$$\partial_{\widehat{S}_\beta} U_\beta(R_\beta, \widehat{S}_\beta) = \frac{1}{1-\gamma}\left\{-\pi_\beta(\widehat{S}_\beta) + \gamma F'(\widehat{S}_\beta)\pi_\beta[F(\widehat{S}_\beta)]\right\}.$$

Thus the first-order condition for maximizing $U_\beta[R_\beta]$ over $S^o_\beta \leq \widehat{S}_\beta < F^{[-1]}(\widehat{R}_\alpha)$ is that

$$\widehat{S}_\beta = \min[S^*_\beta, F^{[-1]}(\widehat{R}_\alpha) - \epsilon].$$

On the other hand, for $R_\alpha > \widehat{R}_\alpha$

$$U_\alpha(R_\alpha) = \int_{\widehat{S}_\alpha}^{R_\alpha} \pi_\alpha.$$

Hence an ϵ-optimal $\widehat{S}_\alpha$ is as small as possible. In particular, the policy profile

$$\{[S^o_\alpha, R^o_\alpha(\kappa)], S^o_\beta\}$$

constitutes a Nash equilibrium. Here the related fixed cost for the α-fleet will be

$$\kappa = \int_{S_\alpha^o}^{R_\alpha^o} \pi_\alpha + \gamma\{U_\alpha(R_\alpha^o) - U_\alpha(S_\alpha^o)\} = \int_{S_\alpha^o}^{R_\alpha^o} \pi_\alpha + \gamma \int_{S_\alpha^o}^{R_\alpha^o} \pi_\alpha.$$

DETERRING THE HIT-AND-RUN INVADER EXPLOITING THE EEZS

The incumbent fleet may have a more powerful tool, with which to tip the balance of competition in its favor. Namely it could exploit the fact that it has the exclusive right to harvest in the EEZs. To illustrate, let us suppose that the migration pattern of a straddling stock is such that its nursery area is in the national waters of an EEZ, and that only a portion of the maturing stock migrates out to the international zone. There of course it is subject to harvest by anyone. After a period of time, but before spawn, the high seas portion moves back to rejoin the remaining stock in the EEZ, where it will be subject only to incumbent harvest.

The home fleet has a long-term interest in this fishery; so that its objective includes the discounted value of anticipated future returns A foreign fleet, which annually seeks out targets-of-opportunity on the high seas, may enter the international zone of this particular fishery, but will harvest here only if the reward for doing so exceeds the potential return from harvesting elsewhere.

A plausible incumbent fleet's response strategy might then be to move pre-emptively into international waters. There it would fish-down the migratory stock, so as to deter the entry of any potential foreign invader. The incumbent could then mitigate the effect of this overharvest by cutting back the scale of its subsequent harvest in the home EEZ. We have modeled this scenario, to examine the trade-offs that are being made. The stock development in this model is illustrated schematically in Figure 6.

Explicitly, the initial recruitment stock R divides into two parts, with a fraction

θ moving into the international zone and the remaining fraction $\phi = 1 - \theta$ remaining in the EEZ. In the upper (international) branch of the diagram, the fractional recruitment θR is fished down to S_θ by the incumbent β-fleet. The foreign α-fleet then enters, but only if the stock level S_θ that it will encounter exceeds a certain threshold level R_α.If it does enter, then it will fish-down the accessible stock to a very low level (since it discounts the future completely), say to $S_\alpha^o << R_\alpha$. Thus the escapement from the high seas fishery will be

$$\widehat{S}_\alpha = \begin{cases} S_\alpha^0 & \text{if } \alpha\text{-fleet enters;} \\ S_\theta & \text{if } \alpha \text{ is deterred.} \end{cases}$$

Within the regional EEZ (shown as the lower branch in the diagram), there is no harvest until the residual straddling stock has returned to home waters, to augment the domestic stock. The home-waters recruitment thus is

$$R_\beta = \widehat{S}_\alpha + S_\phi = \widehat{S}_\alpha + \phi R.$$

Finally, the home β-fleet harvests down to an escapement $S_\beta \leq R_\beta$, a level chosen to achieve the optimal balance between present and future returns.

Within-season payoff to the β-fleet is

$$\int_{S_\theta}^{\theta R} \pi_\theta(x)dx + \int_{S_\beta}^{R_\beta} \pi_\beta(y)dy,$$

the sum of its harvest returns from high-seas and home waters.

If the α-threshold is precisely known and constant, then the β-fleet optimally will always wish to exclude its rival from entry, and will do so if it can – i.e. if

$$S_\theta^0 \leq R_\alpha.$$

We shall concentrate on this case first.

(However we mention in passing the more realistic situation where R_α is stochastic and furthermore cannot be predicted with certainty by the β-fleet. In that circumstance, the β-fleet normally will wish to choose an intermediate level of harvest escapement S_θ, a level at which the α-fleet will sometimes enter and sometimes be deterred.)

It is instructive to compare the outcome of competition with the monopolistic outcome when there is threat of invasion. In either case the fishery evolves quickly to a steady state pattern

$$\{\widetilde{S}_\beta, \widetilde{R}\},$$

with $\widetilde{S}_\beta$ the target escapement level and $\widetilde{R} = F(\widetilde{S}_\beta)$. For simplicity, we assume that the home fleet's harvest payoff, at *any* given stock level S, is always higher at home than on the high seas:

$$\pi_\theta(S) < \pi_\beta(S).$$

This implies that, when there is no threat of invasion, the home fleet will operate monopolistically, exclusively in home waters, and setting an escapement target S^*_β, according to the usual marginal rule that

$$\pi_\beta(S^*_\beta) = \pi_\beta(R^*_\beta) \cdot \gamma F'(S^*_\beta),$$

with

$$R^*_\beta = F(S^*_\beta).$$

On the other hand, when faced by the threat of foreign entry on the high seas, the β-fleet *may* (unless the foreign fleet's entry threshold is extremely high) find it optimal to divert some of its own fishing to international waters, in order to deter the interloper's entry. There are several possibilities, depending on the size of the ratio

$$R_{crit} \triangleq R_\alpha / \theta$$

in (R_α, θ)-parameter space.

If the α-fleet's entry threshold R_α is high and/or the high seas stock fraction is small, so that

$$R^* \leq R_{crit},$$

then the β-fleet can continue to follow it's monopolistic harvest policy without fear of α-entry.

On the other hand, if R_{crit} is small, then the α-fleet's competitive position is strong. In this case, total α-exclusion will require establishing a new escapement target[3]

$$S_{\beta}^{\#}(R_{crit}, \theta),$$

and transferring enough β-harvest to the high seas that the β-fleet's *high seas* escapement level becomes

$$S_{\theta}^{\#} = R_{\alpha}.$$

(This can be achieved if $S_{\theta}^{\#}$ exceeds S_{θ}^{o}, the β-fleet's high-seas break-even level.)

The *Home-ground* target escapement now is determined by a new marginal rule, namely

$$\pi_{\beta}(S_{\beta}^{\#}) = \left[\theta \cdot \pi_{\theta}(\theta R^{\#}) + \phi \cdot \pi_{\beta}(R_{\beta}^{\#})\right] \cdot \gamma F'(S_{\beta}^{\#}),$$

where

$$R^{\#} = F(S_{\beta}^{\#}), \quad \text{and } R_{\beta}^{\#} = R_{\alpha} + \varphi \cdot R^{\#}.$$

This rule equates the return from harvest of the marginal unit at the end of the current season with the return from maintaining that marginal unit in the brood stock, to enhanced recruitment on both high seas and home ground during the following season.

For this marginal rule to be applicable, there must be positive harvest in both branches of the fishery; hence necessarily the low-threshold rule is applicable only when

$$R_{crit} < R^{\#}(R_{crit}, \theta).$$

[3] #-notation is used only when the β-fleet must harvest both at home and on the high-seas; that is, when facing strong competition, see Figure 7.

Since always $R^{\#}(R_{crit}, \theta) < R^*$, there is a level $R_{crit} = R^{\#}_{crit}(\theta)$ at which high-seas β-harvest pinches out. Within the interval

$$R^{\#}_{crit}(\theta) < R_{crit} < R^*$$

neither the $S^{\#}_{\beta}(R_{crit})$ target nor the S^*_{β} target is appropriate.

Instead a third target escapement $\widehat{S}_{\beta}$ becomes appropriate. It satisfies the relations

$$\widehat{S}_{\theta} = \theta R_{\alpha}$$

implying no high-sea harvest and

$$\widehat{R} = F(\widehat{S}_{\beta}) = R_{crit};$$

or equivalently

$$\widehat{S}_{\beta} = F^{-1}(R_{crit}).$$

This equilibrium $\widehat{R}(R_{crit})$ obviously coincides with, respectively, $R^{\#}_{crit}(\theta)$ or R^* at the left and right endpoints of its interval of applicability.

We have pointed out that the incumbent β-fleet's position may conceivably be quite weak–indeed that when

$$R_{\alpha} < S^{o}_{\theta}$$

it will be unable to deter α-entry without setting its high seas escapement at a level below it's break-even S^{o}_{θ}. While this might be acceptable on a few occasions (to prevent a catastrophic stock draw-down by a one-time potential invader), an on-going policy of preemptory high-seas entry would be a very expensive form of insurance against an ongoing threat. The whole picture of the hit-and-run model is illustrated in Figure 7.

But the home fleet might develop an ability to respond quickly and aggressively, only to each *actual* invasion. The game would then become one of bluff: If the regional coalition could develop a credible reputation for aggressive response, it might well frighten off potential interlopers. Such a policy would also have its costs: Not only would it require the maintenance of an expensive response capability, but also its very implementation would require a stock draw-down that might be highly detrimental to future stock productivity. Thus there would remain an incentive to develop a more effective means of deterrence, or to work out a cooperative solution.

Details of the hit-and-run model

Let us now look at the more technical details of the hit-and-run model. We begin with the dynamic programming equation (DPE), which assumes no α-fleet entry:

$$V[R] = \max_{S_\theta, S_\beta} \left\{ \int_{S_\theta}^{\theta R} \pi_\theta + \int_{S_\beta}^{S_\theta + \phi R} \pi_\beta + V[F(S_\beta)] \right\},$$

where

$$\begin{aligned} S_\theta^o &\leq S_\theta \leq \theta R \text{ and} \\ S_\beta^o &\leq S_\beta \leq R_\beta = S_\theta + \phi R. \end{aligned}$$

We maintain the assumption that for all S

$$\pi_\theta(S) < \pi_\beta(S).$$

This has the following consequence: Consider a pair of controls $\{S_\theta, S_\beta\}$, *feasible* in the sense of satisfying the above control-constraints. Suppose also that $S_\theta < \theta R$, so that there is a high-seas component to the specified harvest. Then the payoff can always be increased by increasing the high-seas escapement S_θ–that is, by transferring a part (or all) of the original high seas harvest to home waters. Indeed the component that is transferred from the bottom high seas stock will be harvested instead to the top level of the home waters stock, and

$$\pi_\theta(S_\theta) < \pi_\beta(S_\theta + \phi R).$$

With this in mind, consider now the situation of an unchallenged monopolist β-fleet. Clearly, from the above considerations, it should restrict its harvest *entirely* to home waters. Therefore its policy problem reduces to solving the reduced DPE

$$V[R] = \max_{S_\beta} \left\{ \int_{S_\beta}^{R} \pi_\beta + V[F(S_\beta)] \right\},$$

with

$$S_\beta^o \le S_\beta \le R.$$

The well-known solution is most-rapid approach to the optimal target escapement S_β^*, i.e.

$$S_\beta = \min[R, S_\beta^*],$$

where

$$\gamma F'(S_\beta^*) = \pi(S_\beta^*)/\pi_\beta[F(S_\beta^*)].$$

However, when the β-monopolist is challenged–i.e. when there is a potential for invasion by an α-fleet–an response adequate to prevent such entry must satisfy an additional constraint: Namely, exclusion requires that the high-seas stock level faced by the potential invader must lie below the invader's entry threshold:

$$S_\theta \le R_\alpha.$$

It may be possible to meet this additional constraint by harvesting exclusively in home waters, i.e. by setting

$$S_\theta = \theta R.$$

But the new constraint then implies that

$$\theta R \le R_\alpha,$$

or equivalently that

$$R \le R_{crit} \triangleq R_\alpha/\theta.$$

Consequently it requires that the home ground escapement R should fall below the critical level R_{crit}. In particular, the monopolistic policy, of most-rapid approach to the steady-state $\{S_\beta^*, R^*\}$, will meet the new requirement *only if* the critical ratio $R_{crit} = R_\alpha/\theta$ is sufficiently large that

$$R^* \leq R_{crit}.$$

(Note that R^* itself is independent of both R_α and θ.) Whenever this condition holds, the monopolistic policy remains optimal

The case when $R_{crit} < R^*$.—

When $R_{crit} < R^*$, the incumbent fleet must seek an alternative policy, one which involves also some harvesting on the high seas. High-seas harvesting will be necessary only in seasons when recruitment R is large compared to the critical level, i.e. when

$$R_{crit} < R,$$

so that $R_\alpha < \theta R$. Furthermore, since home-waters harvesting is more efficient, high-seas harvest should be limited to the *minimum* necessary for α-exclusion (Only in that case can payoff fail to be improved by shifting some harvest to home waters.)

Hence high-seas β-escapement S_θ must necessarily satisfy

$$S_\theta = \widetilde{S}_\theta \triangleq \min[\theta R, R_\alpha].$$

This implies that

$$R_\beta = \widetilde{R}_\beta(R) \triangleq \begin{cases} R_\alpha + \phi R & \text{if } R_{crit} < R \\ R & \text{if } R \leq R_{crit} \end{cases},$$

depending on whether or not high seas β-harvest is necessary.

These considerations lead to formulation of an optimization problem for a *restricted* two-location harvest. In dynamic-programming format,

$$V[R] = \max_{S_\beta} \left\{ \int_{\widetilde{S}_\theta}^{\theta R} \pi_\theta + \int_{S_\beta}^{\widetilde{R}_\beta(R)} \pi_\beta + \gamma V[F(S_\beta)] \right\}.$$

The analysis of this DP equation falls into four distinct cases, depending on the current recruitment $R$and the (R_α, θ) parameter configuration.

Configuration 1) The β-fleet harvests on the high seas but does not harvest at home: Thus

$$R_{crit} < R \text{ and } S_\beta = \widetilde{R}_\beta(R).$$

From this,

$$\begin{aligned} S_\theta &= R_\alpha, \text{ and} \\ S_\beta &= R_\alpha + \phi R. \end{aligned}$$

The DPE becomes

$$V[R] = \left\{ \int_{R_\alpha}^{\theta R} \pi_\theta + \gamma V[F(R_\alpha + \phi R)] \right\}.$$

The dynamic asset-value equation thus is

$$\lambda(R) = \theta \pi_\theta(\theta R) + \gamma \phi F'[S_\beta] \lambda[F(S_\beta)],$$

and there is no associated steady-state.

Configuration 2) The β-fleet harvests neither on high seas nor at home: Thus

$$R \leq R_{crit} \text{ and } S_\beta = \widetilde{R}_\beta(R).$$

From this,

$$\begin{aligned} S_\theta &= \theta R, \\ S_\beta &= \widetilde{R}_\beta(R) = R. \end{aligned}$$

The DPE becomes

$$V[R] = \gamma V[F(R)],$$

and the dynamic asset-value equation becomes

$$\lambda[R] = \gamma\lambda[F(R)].$$

Again there is no steady-state associated with case 2.

Configuration 3) The β-fleet harvests both on high seas and in home waters: Thus

$$R_{crit} < R \text{ and } S_\beta < \widetilde{R}_\beta(R)$$

Since $R_{crit} < R$, .therefore exclusion requires $S_\theta = R_\alpha$ Also

$$S_\beta < \widetilde{R}_\beta(R) = R_\alpha + \phi R.$$

Hence the DPE reduces in this case to

$$V[R] = \max_{S_\beta} \left\{ \int_{R_\alpha}^{\theta R} \pi_\theta + \int_{S_\beta}^{R_\alpha + \phi R} \pi_\beta + \gamma V[F(S_\beta)] \right\}.$$

Differentiating the bracketed quantity in this DP equation by the control S_β yields the optimality equation

$$\gamma F'(S_\beta^\#) = \pi_\beta(S_\beta^\#)/\lambda[F(S_\beta^\#)].$$

Note that this optimal escapement is constant, independent of R within case 1. Likewise choosing $S_\beta = S_\beta^\#$ and differentiating the DPE by the state variable R yields the dual dynamic equation, for the marginal asset-value $\lambda(R) \triangleq d/dV(R)$:

$$\lambda(R) = \pi_{mix}(R) \triangleq \theta\pi_\theta[\theta R] + \phi\pi_\beta[R_\alpha + \phi R)].$$

If there exists a *steady-state* $\{S_\theta^\#, S_\beta^\#, R^\#\}$ conforming to this case, and for which

$$\begin{aligned} R^\# &= F[S_\beta^\#] \\ S_\theta^\# &= R_\alpha < \theta R^\#, \end{aligned}$$

then necessarily

$$S_\beta^\# = S_\beta^\#(R_\alpha, \theta)$$

is given by

$$\gamma F'(S_\beta^\#) = \frac{\pi_\beta(S_\beta^\#)}{\theta\pi_\theta(\theta R^\#) + \phi\pi_\beta(R_\alpha + \phi R^\#)}$$

Observe that

$$S_\beta^\#(R_\alpha, \theta) < S^*.$$

Indeed whenever $S_\theta < \theta R$

$$\partial_{S_\theta}\{:\} = -\pi_\theta(S_\theta) + \pi_\beta(R_\beta) > \pi_\theta(S_\theta) + \pi_\beta(S_\theta) \geq 0,$$

and hence that

$$\pi_{mix}(R) < \theta\pi_\beta[R_\beta] + \phi\pi_\beta[R_\beta] < \pi_\beta[R^\#(R_\alpha)],$$

Comparing the defining equations for $S_\beta^\#(R_\alpha)$ and S^*, we conclude that indeed $S_\beta^\#(R_\alpha) < S^*$.

But then also

$$S_\beta^\#(R_\alpha) < R^\# < K,$$

confirming that the triple $\{S_\theta^\#, S_\beta^\#, R^\#\}$, if it conforms to the conditions defining case 1, does indeed determine a steady state. Furthermore, for *any* , one has optimally that $S_\beta(R) = S_\beta^\#$. Comparing also configurations 1 and 2, we conclude that for any initial recruitment R,

$$\begin{aligned} S_\theta &= \min[R_\alpha, \theta R^\#]; \\ S_\beta &= \min[S_\theta^\#, R_\alpha + \phi R^\#] \end{aligned}$$

Configuration 4) The β-fleet does not harvest on the high seas, but only at home: Thus

$$R \leq R_{crit} \text{ and } S_\beta < \widetilde{R}_\beta(R).$$

Since $R \leq R_{crit}$, therefore $S_\theta = \theta R$ and $\widetilde{R}_\beta(R) = R.$. Also

$$S_\beta < R \leq R_{crit}.$$

The DPE therefore becomes

$$V[R] = \max_{S_\beta < R} \left\{ \int_{S_\beta}^{R} \pi_\beta + \gamma V[F(S_\beta)] \right\}$$

The optimality equation is again

$$\gamma F'(S_\beta) = \pi_\beta(S_\beta)/\lambda[F(S_\beta)],$$

and the asset-value equation becomes

$$\lambda(R) = \pi_\beta(R).$$

Consider a generating triple, $\{S_\theta, S_\beta, R\}$, with

$$\begin{aligned} R &= F[S_\beta] \leq R_{crit} \\ S_\theta &= \theta R \geq R_\alpha, \end{aligned}$$

There is a unique steady-state corresponding to *each* $R \leq R_{crit}$. To determine which of these will be optimal for the given R_{crit}, one returns to consideration of the DPE. The additional steady-state constraint on S_β is that

$$S_\beta = F^{-1}[R] \leq F^{-1}[R_{crit}].$$

The optimization *inequality* is that

$$\partial_{S_\beta}\{:\} = -\pi_\beta(S_\beta) + \gamma F'(S_\beta)\lambda[F(S_\beta)] \geq 0$$

The *global* (or unconstrained) steady-state, with $R = F(S_\beta)$, is at $\{S_\beta^*, R^*\}$, and the partial derivative is positive to the left of R^*. That is, R should be chosen as large as possible, consistent with exclusion of the α-fleet. Hence, provided that $R_{crit} \leq R^*$, the optimal choice consistent with case 2 (harvesting only at home) is the steady-state generated by $\{\widehat{S}_\theta, \widehat{S}_\beta, \widehat{R}\}$, where

$$\begin{aligned}\widehat{R} &= R_{crit},\\ \widehat{S}_\beta &= F^{-1}[\widehat{R}], \text{ and}\\ \widehat{S}_\theta &= \theta\widehat{R}.\end{aligned}$$

Synthesis of Results

Our analysis has revealed that, whenever the incumbent β-fleet is able to exclude entry of the potential invader α-fleet, the optimal β-policy is most-rapid approach to a stable steady-state which is determined by the critical recruitment $R_{crit} = R_\alpha/\theta$ as follows:

A) If $R_{crit} \geq R^*$, then the monopolistic policy

$$\begin{aligned}S_\theta &= \theta R; \text{ and}\\ S_\beta &= \min[S^*_\beta, R]\end{aligned}$$

is optimal, and leads to the stable steady state $\{S^*_\theta, S^*_\beta, R^*\}$, with $R^* = F(S^*_\beta)$ and $S^*_\theta = \theta R^*$.

B) If $R_{crit} \leq R^\#(R_\alpha, \theta)$ then the two-region harvest policy

$$\begin{aligned}S_\theta &= \min[R_\alpha, \theta R^\#(R_\alpha, \theta)];\\ S_\beta &= \min[S^\#_\theta(R_\alpha, \theta), R_\alpha + \phi R^\#(R_\alpha, \theta)]\end{aligned}$$

is optimal, and leads to the stable steady state $\{S^*_\theta, S^*_\beta, R^*\}$, where $R^\# = F(S^\#_\beta) \leq R_{crit}$ and $S^\#_\theta = \theta R^\#$

C) If $R^\#(R_\alpha, \theta) < R_{crit} < R^*$ then the policy

$$\begin{aligned}S_\theta &= \min[\theta R_{crit}, \theta R]; \text{ and}\\ S_\theta &= \min[F^{-1}(R_{crit}), R]\end{aligned}$$

is optimal, and leads to the stable steady state $\{\widehat{S}_\theta, \widehat{S}_\beta, \widehat{R}\}$, where $\widehat{R} = R_{crit}$, $\widehat{S}_\beta = F^{-1}(R_{crit})$ and $\widehat{S}_\theta = \theta R_{crit}$.

CONCLUSIONS

Static and dynamic analysis both predict that barriers to entry into a regionally managed straddling-stock fishery can indeed be constructed within the harvesting sector, but that the erection of such barriers will usually have substantial negative consequences, both for biological sustainability and economic efficiency. An established Regional Management Organization does possess certain strategic advantages which it can exploit in order to internalize competition. These include the first-mover advantage of incumbency and exclusive harvesting rights within the home-countries' EEZs. But normally these advantages can be invoked only at high cost.

The analysis thus lends support to the thesis that the leverage needed to enforce regional management control must be sought elsewhere, other than through the direct application of economic power within the harvesting sector alone.

REFERENCES

[1] Jaquette, D.L., 1974, A discrete-time population-control model with setup cost, *Operations Research* **22**: 298 - 303.

[2] Munro, G.R., 1999, An Economic Review of the UN Agreement for the Implementation of the UN Convention on the Law of the Sea of 10th December 1982 Relating to the Conservation and Management of Straddling and Highly Migratory Fish Stocks (Conference on the Management of Straddling and Highly Migratory Fish Stocks and the UN Agreement, Norwegian School of Economics and Business Management, Bergen, May 1999).

[3] Reed, W.J., 1974, A stochastic model for the economic management of a renewable

animal resource, *Mathematical Biosciences* **22**: 313 - 337.

[4] Tirole, J., 1988, *The theory of industrial organization* (MIT Press, Cambridge Mass.).

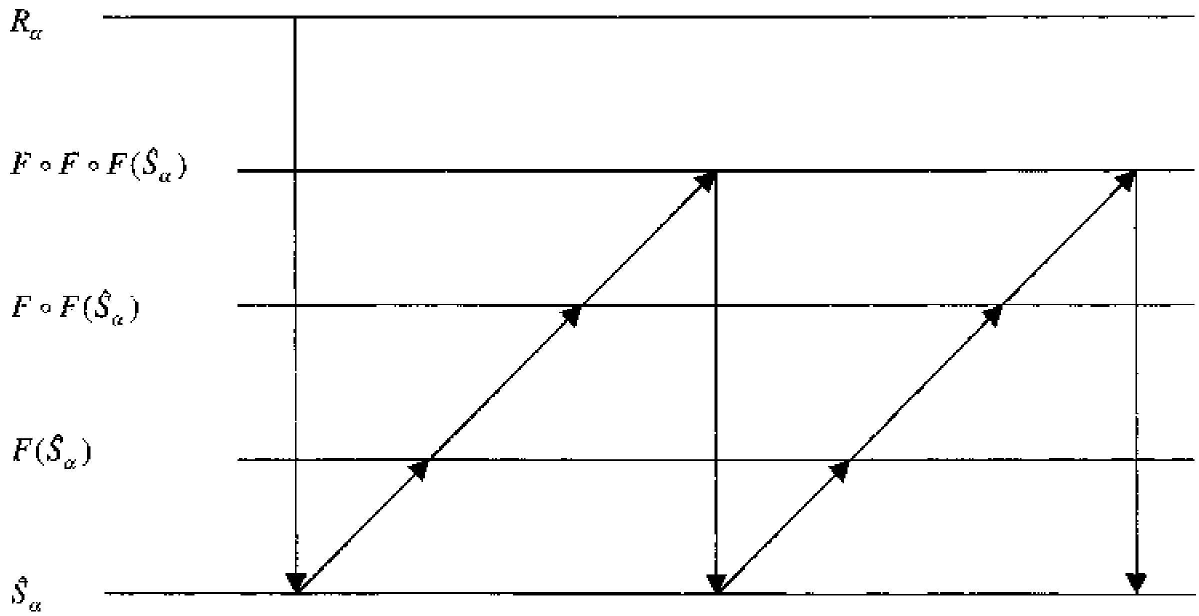

Figure 1.
Monopolistic harvesting. The case of $N = 3$.

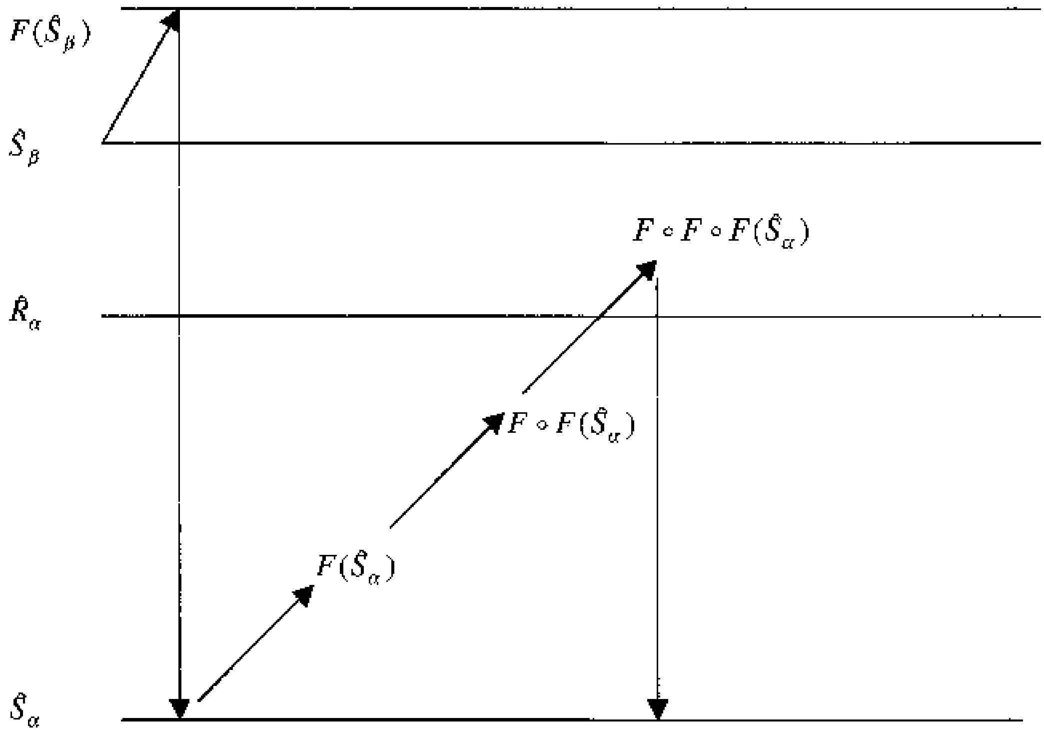

Figure 2. The repeating pulse cycle in the case with α-fleet dominance. $N = 3$.

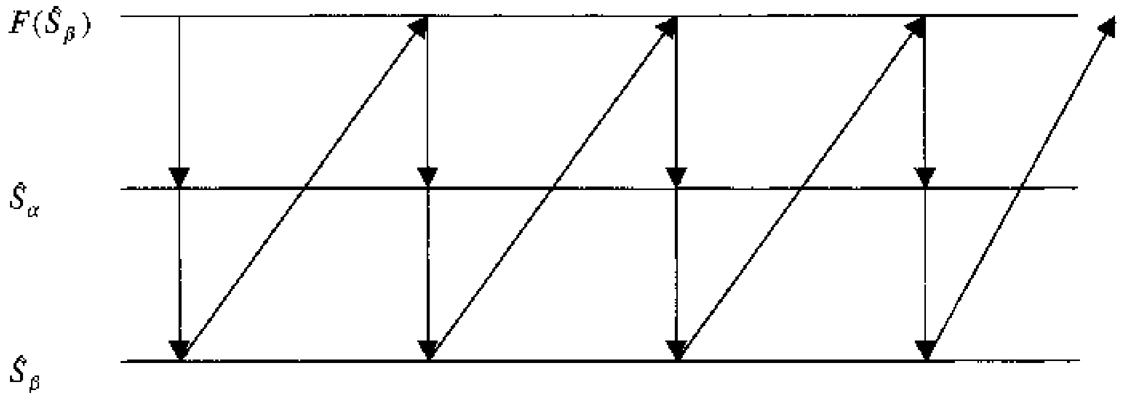

Figure 3. The repeating pulse cycle in the coexistence case for $N = I$.

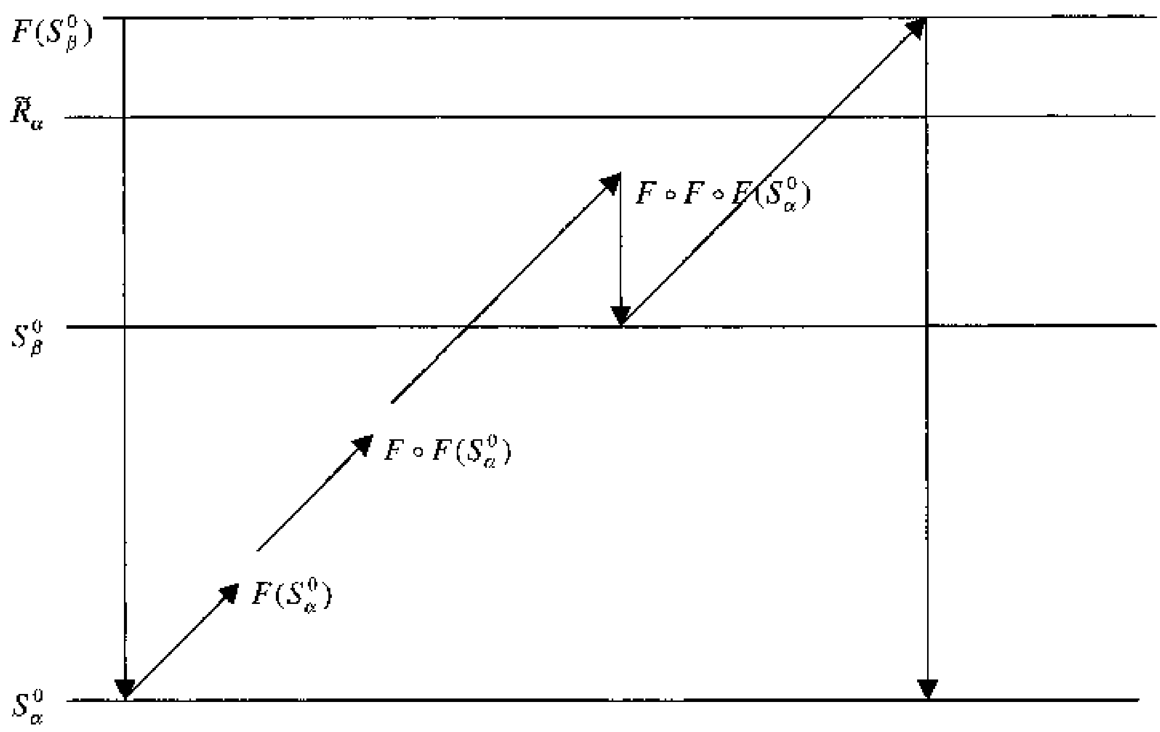

Figure 4. The repeating pulse cycle in the coexistence case. $N = 4$.

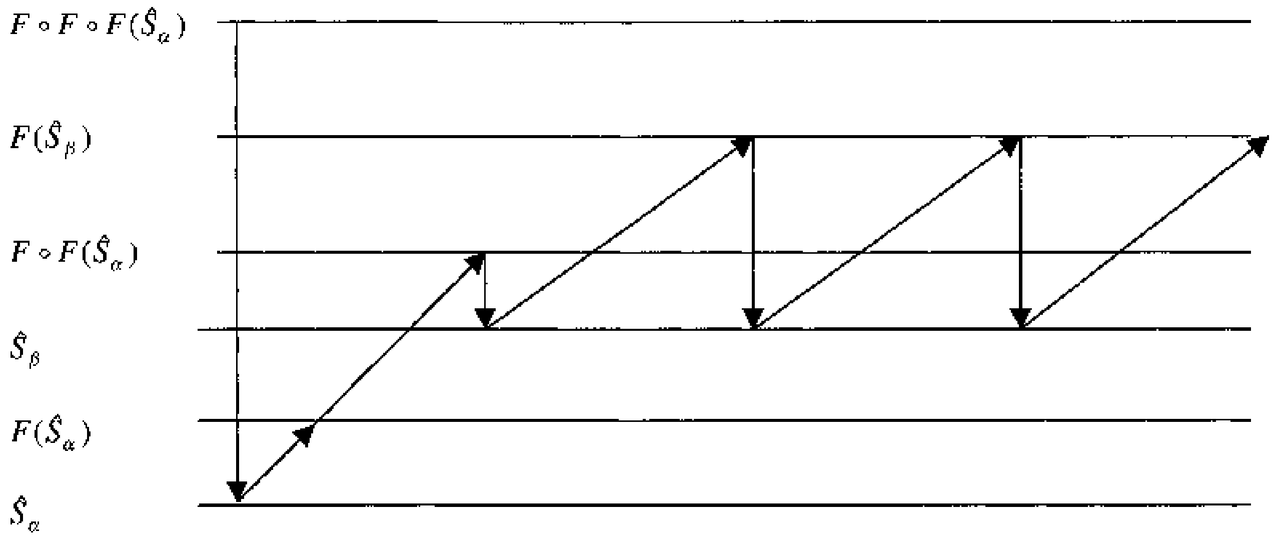

Figure 5.
The repeating single-period pulse cycle in the case with β-fleet dominance.

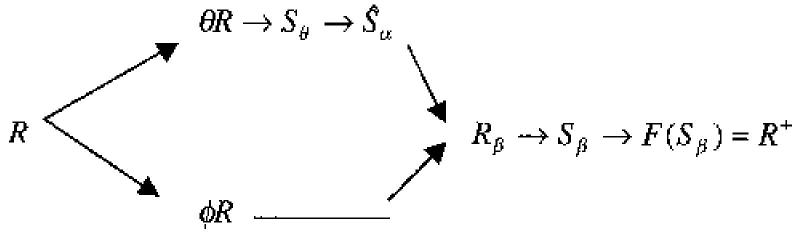

Figure 6.
Stock development from one period to the next in the hit-and-run model.

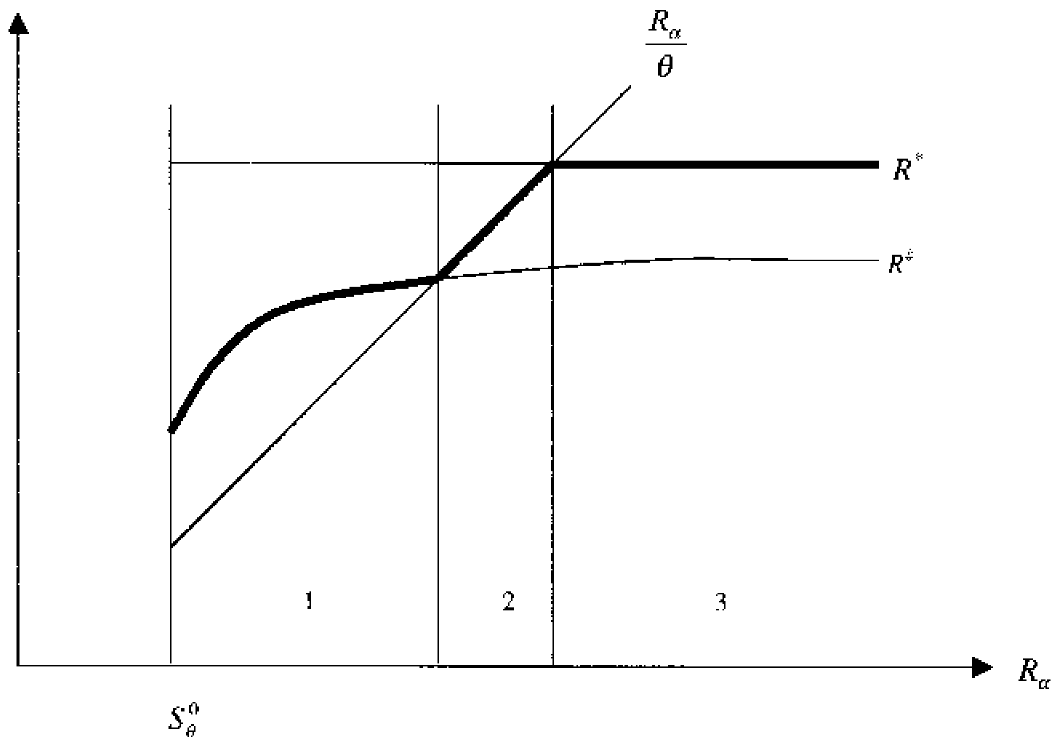

Figure 7.
Area 1: Strong competition. Home fleet harvests both at home and on the high seas.
Area 2: Medium competition. Home fleet harvests only on home ground.
Area 3: Weak competition. The home fleet can act as a monopolist.