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Fish Wars on the High Seas: A Straddling Stock Competition Model

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A Straddling Stock Competition Model

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Abstract

The post World War II era saw the development of powerful self-contained fishing fleets, so-called *distant-water fleets (DWFs),* which roamed the world's oceans, seeking out rich harvesting targets wherever they might be found. These fleets practiced pulse fishing, harvesting a given fish stock intensively, then moving on, leaving a depleted fishery which might require many years to recover.

With the creation in the 1980s of coastal states' extended economic zones (EEZs), to manage fisheries out to 200 miles from the shore, it was hoped that the DWFs would close down. But the ranges of many important commercial fish stocks straddle the boundaries of several EEZs, and continue out into international waters. Thus the consequence of creating the EEZs has been to encourage development of coastal countries' national fleets, while the DWFs continue to harvest in international waters. Since these separately managed fleets are harvesting from a common pool resource, this situation sets up a destructive confrontation, a classic "fish war".

Here we model the fish war between a DWF and a regionally-based coalition of coastal states, operating out of their EEZs. The outcome is a again a pulse fishery, but one which may be even more destructive than was the former situation, when the DWF was unopposed.

Finally we point out the relevance of the fish war model to the issue of creating effective multinational Regional Fisheries Management Organizations–a necessary step for achieving sustainable benefit from the harvest of the regional seas.

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INTRODUCTION[1][2]

The 1982 U.N. Convention on the Law of the Sea (LoS) established national Extended Economic Zones (EEZs), for the management of marine fisheries within 200 miles of the shores of coastal seas. Prior to that time, powerful distant-water fishing fleets (DWFs) had roamed the coastal seas, seeking to exploit targets of opportunity worldwide . 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 stocks to recover before returning to exploit them again.

With the establishment of the EEZs, it was expected that these wide-ranging fleets would simply be replaced by smaller national fleets of coastal states, and that national authorities would be able to constrain harvests to moderate sustainable levels. Instead the older vessels often were not decommissioned, leading to a worldwide phenomenon of excessive harvesting capacity. Furthermore, the ranges of many harvested stocks (so-called "straddling stocks") are not confined to a single EEZ, and indeed often extend beyond the coastal areas and onto the high seas. Hence distant water fleets often simply redirected their harvesting efforts to the high seas portion of the previously exploited straddling stocks' ranges. The result has been even greater overharvesting, and severe depletion of many of the world's most important commercial fish stocks.

An example is provided by the rich groundfish stocks in the Bering Sea, harvested prior to LoS mainly by the US, Russia, and Japan [Miles and Burke 1989]. 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

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fleet, now banished from the EEZs, concentrated on the Doughnut Hole, and in a few years has badly depleted the stock there. There is at present little interest in further fishing in the Hole, but restraint by the US. and Russian fleets can be expected to rebuild the stocks. Thus in future this fishery can expect to attract a pattern of distant water fleet pulse-fishing.

A second example concerns European Union DWF harvest of groundfish stocks in the Grand Banks, off Newfoundland [Gordon and Munro 1996]. Since creation of the Canadian EEZ, these fleets have been confined to harvesting in limited high seas portions of the banks. These severe constraints, plus new limitations in harvesting possibilities in European home waters, have led to ongoing disputes between the EU and Canada. Indeed, continuing high seas harvesting of depleted stocks, especially by Spanish vessels, led ultimately to dramatic high seas confrontations between Canadian authorities and vessels of the DWF.

In response to these and similar situations worldwide, the world's fishing nations adopted in 1995 the U.N. Fish Stocks Agreement, spelling out principles for conservation and management for straddling stocks and highly migratory stocks. The Agreement specifies that all harvesting of such a fish stock, 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 (RFMO). 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 RFMO, to declare a willingness to join and to enter into negotiations over mutually acceptable terms of entry.

Once a Regional Management Organization has been established, the original national 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. However, the Agreement provides to the Regional Organization no coercive enforcement powers, to exclude non-member's harvest or to 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. 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.

Two problems in particular have been cited: The first, 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, called by the "new member problem", [Kaitala and Munro, 1993] concerns the inherent difficulties of negotiating mutually acceptable terms of entry for a potential new member, specifying its 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's best strategy might be delay entry into the RFMO, continuing to harvest profitably while demonstrating the strength of its bargaining position.

In this article we shall focus on the new member problem. More specifically, we shall examine the dynamics of a long-run competition, over harvest of a geographically dispersed fish stock, between a regionally based fleet, coordinated by a RFMO, and a centrally managed distant water fleet, operating on the high seas. As in most current situations (including the two examples cited above) the regional fleet does not venture onto the high seas, but confines its harvest to the EEZs of its member states. While, in the model, the DWF has remained outside of the RFMO, the prospect of its continuing presence in the fishery may provide it a convincing "threat strategy" for the eventual hard bargaining over its possible entry into the RFMO.

We begin by reviewing and expanding on analysis of a model, by Reed (1974) and Jaquette (1974). This model has been applied to explain the earlier pulse fishing pattern by an unopposed distant-water-fleet, prior to the creation of coastal states' Extended Economic Zones. We then expand upon this decision model, turning it into a game between two competing fleets, a DWF and a regionally-based fleet which is coordinated by a RFMO. It is assumed that both fleets maintain long-term interests in participating in the fishery, but will do so independently, as long-term competitors. Finally we return to the new member problem, briefly discussing the implications of the competition model's outcome for the prospects of a cooperative resolution.

THE BASIC FISHERY MODEL: OPTIMAL CENTRALIZED MANAGEMENT

In the simplest multiseasonal 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*, denoted by R. The *harvested biomass* during the season is denoted by H. Finally, the biomass remaining at the end of the season is called *escapement*, and is denoted by S. Thus

$$S = R - H.$$

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*

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

Thus, schematically, the stock level is seen to evolve seasonally according to

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

Here, for simplicity, we will assume that $F(S)$ is an increasing concave function with $F(0) = 0$, and assume for this growth function a *carrying-capacity* $K > 0$, such that

$$F(K) = K.$$

An unharvested stock will converge over time to a steady state at K .

Throughout this section, suppose that a single centralized authority controls the harvest. Typically the authority would set annual harvests to maximize the discounted sum of *net annual returns* $\Pi(R, S)$, over an infinite time horizon:

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

During each harvesting season, the stock will be drawn down gradually, from initial R to final S, with the net *variable return rate*, per-unit of landings,

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

depending on current within-season stock level x. Here p is a fixed unit price for the landed harvest and $C(x)$ is the unit *variable 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. Thus there will be a unique break-even *bionomic stock level* $S^o \geq 0$, such that

$$C(S^o) = p$$

and below which harvesting is unprofitable. Typically

$$C(x) = \frac{c}{x},$$

in which case the bionomic stock level is

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

There may also be a *fixed cost of harvest*, denoted κ, which is applied only in those seasons when the fleet actually harvests, i.e. when $H > 0$. Thus in general the net seasonal return to harvest is

$$\Pi(R, S; \kappa) = \begin{cases} \int_S^R \pi(x)dx - \kappa & if\ R > S; \\ 0 & if\ R = S. \end{cases}$$

For a *regionally-based fleet*, it will be appropriate to assume that there is no significant fixed cost of harvest , but only variable costs. Thus $\kappa = 0$, and the net return from the entire season's harvest is

$$\Pi(R, S; 0) = \int_S^R \pi(x)dx = pH - \int_S^R C(x)dx.$$

According to standard analysis [e.g. Clark, 1990)] optimal management requires determining an optimal *target escapement level,* S^*, which is independent of t, and adopting an escapement policy

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

That is, always harvest down to the target level S^* whenever recruitment exceeds it; otherwise do not harvest, but allow the stock to grow until it rises above S^*.

The optimal S^* satisfies a marginal rule (the so-called "golden rule")

$$\pi(S^*) = \gamma F'(S^*) \cdot \pi[F(S^*)], \tag{1}$$

which equates the marginal value of the final unit harvested in a given season to the foregone value of retaining it in the stock, to contribute to the following year's recruitment.

In contrast, for a centrally managed *distant-water fleet,* it will be appropriate to include a positive fixed cost of entry κ in the seasonal harvest return. This fixed cost may be justified as the cost of travel from a distant home port, or as the opportunity cost of foregone alternative harvesting options, elsewhere on the high seas.

With a positive fixed cost of entry, a somewhat more complicated harvesting policy is appropriate Indeed, the 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 fixed-cost which entry would trigger. (See Reed [1974] and Jaquette [1974]. whose work applied more generally to stochastic growth models.)

Explicitly, Reed and Jaquette proved that the optimal harvesting policy is of a type called an $(\widehat{S}, \widehat{R})$*-policy,* or *threshold policy,* one which specifies both a *target escapement* and a higher *harvest threshold* $\widehat{R}$ such that

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

Such a policy requires, for given recruitment R, that escapement be

$$S = \begin{cases} \widehat{S}, & if \;\; \widehat{R} \leq R \\ R, & if \;\; R < \widehat{R}. \end{cases}$$

Thus the policy is to harvest down to the target level $\widehat{S}$ if recruitment exceeds the trigger level $\widehat{R}$, but not to harvest if the recruitment is below that trigger level. This result of Reed and Jaquette is quite general, applying for example when the stock growth function $F(S)$ is stochastic.

The threshold recruitment level is set so that at that level the fleet optimally will be indifferent between entering or not entering. Because of the gap between $\widehat{S}$

and $\widehat{R}$ when $\kappa > 0$, such a policy can result in a *pulsed* harvesting pattern. That is, harvesting may not occur in every season but will recur only when recruitment exceeds the threshold. For the deterministic model being studied here, this recurrence pattern is easily seen to be periodic. Since we have not seen elsewhere an analysis of this periodic pattern, and since some of the analysis will apply also to our subsequent game model, we shall describe it in detail.

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

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

Furthermore, the dynamic trajectory of the fish stock under optimal harvesting will lead to a cyclic steady-state harvesting pattern of period N. For example, for $N = 3$ and initial recruitment $R > \widehat{R}$, 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* $(\widehat{S}, \widehat{R})$*-policy.*

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

$$U[F^{[N]}(\widehat{S})] = \frac{1}{1 - \gamma^N} \left\{ \int_{\widehat{S}}^{F^{[N]}(\widehat{S})} \pi - \kappa \right\}. \tag{2}$$

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

$$U[R] = \int_{F^{[N]}(\widehat{S})}^{R} \pi + U[F^{[N]}(\widehat{S})] = \int_{F^{[N]}(\widehat{S})}^{R} \pi + \frac{1}{1-\gamma^N}\left\{\int_{\widehat{S}}^{F^{[N]}(\widehat{S})} \pi - \kappa\right\}. \quad (3)$$

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

$$\partial_{\widehat{S}} U(R,\widehat{S}) = \frac{1}{1-\gamma^N}\left\{\gamma^N \frac{d}{d\widehat{S}} F^{[N]}(\widehat{S}) \cdot \pi[F^{[N]}(\widehat{S})] - \pi(\widehat{S})\right\}.$$

Optimization occurs where

$$\partial_{\widehat{S}} U(R,\widehat{S}) = 0,$$

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

$$\gamma^N \frac{d}{d\widehat{S}} F^{[N]}(S^{*N}) = \frac{\pi(S^{*N})}{\pi[F^{[N]}(S^{*N})]} \quad (4)$$

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

For a fixed value of N, and hence of $\widehat{S} = S^{*N}$,there corresponds an interval of possible values of κ, corresponding to the interval of possible values of the threshold recruitment $\widehat{R} = R^{*N}$,which must lie on the interval

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

As noted above, for *any* $(\widehat{S}, \widehat{R})$ policy, $\widehat{R}$ is characterized by the requirement of continuity of the utility function $U(R)$ at that recruitment level. Thus, on the one hand, if immediate harvest is not triggered,

$$U[\widehat{R}] = \gamma U[F(\widehat{R})] = \gamma \int_{F^{[N]}(\widehat{S})}^{F(\widehat{R})} \pi + U[F^{[N]}(S)],$$

using equation (3). On the other hand, if immediate harvest is triggered,

$$U(\widehat{R}) = \left[\gamma \int_{\widehat{S}}^{\widehat{R}} \pi - \kappa\right] + \gamma U[F(\widehat{S})] = \cdots = \left[\gamma \int_{\widehat{S}}^{\widehat{R}} \pi - \kappa\right] + \gamma^N U[F^{[N]}(\widehat{S})].$$

Substituting in the explicit expression (2) for utility at $F^{[N]}(\widehat{S})$, and solving for κ, gives

$$\kappa = \frac{1-\gamma^N}{1-\gamma}\left[\int_{\widehat{S}_\alpha}^{\widehat{R}_\alpha} \pi_\alpha - \gamma \int_{\widehat{S}_\alpha}^{F(\widehat{R}_\alpha)} \pi_\alpha\right] + \gamma^N \int_{\widehat{S}_\alpha}^{F^{[N]}(\widehat{S}_\alpha)} \pi_\alpha. \tag{5}$$

This expression determines κ as a function of $\widehat{S}$, N and $\widehat{R}$, monotone increasing for $\widehat{R}$ on the above interval. Equivalently, for given index N and target $\widehat{S}$, the threshold $\widehat{R}$ is a monotone increasing function of κ on the interval

$$\kappa_N^- \leq \kappa < \kappa_N^+.$$

where

$$\begin{aligned}
\kappa_N^- &= \frac{1-\gamma^N}{1-\gamma}\left[\int_{\widehat{S}}^{F^{[N-1]}(\widehat{S})} \pi - \gamma \int_{\widehat{S}}^{F^{[N]}(\widehat{S})} \pi\right]; \quad \textit{and} \\
\kappa_N^+ &= \frac{1}{1-\gamma}\left[\left(1-\gamma^{(N+1)}\right)\int_{\widehat{S}}^{F^{[N]}(\widehat{S})} \pi - \gamma(1-\gamma^N)\int_{\widehat{S}}^{F^{[N+1]}(\widehat{S})} \pi\right].
\end{aligned} \tag{6}$$

Summarizing, for a sole-operator optimal harvest of period N, the target escapement is $\widehat{S} = S^{*N}$, given by (4). The threshold level $\widehat{R} = R^{*N}(\kappa^{*N})$ is a monotone increasing function of $\kappa = \kappa^*$ on the interval

$$\kappa_N^{*-} \leq \kappa^* < \kappa_N^{*+},$$

whose endpoints are given by equation (6). $R^{*N}(\kappa^{*N})$ itself is given implicitly by equation (5), where $\kappa = \kappa^*$ and $\widehat{S} = S^{*N}$.

THE STRADDLING STOCK COMPETITIVE MODEL

In this model, two centrally managed fleets are engaged in a competitive harvest: The challenger α-fleet is a distant water fleet, harvesting on the high seas, with a fixed cost κ for entering the fishery during any particular season. The incumbent regional β-fleet has no fixed costs, but confines its harvesting to the RFMO's coastal

EEZs. Each season the stock is harvested sequentially, first on the high seas by the distant water α-fleet, which reduces the initial high seas α-recruitment R_α to a high seas escapement

$$S_\alpha = \mathbb{S}_\alpha(R_\alpha).$$

This residual stock migrates into the EEZs, where it becomes the recruitment to the regional β-fleet harvest:

$$R_\beta = S_\alpha.$$

The β-fleet now harvests its available stock down to the season's final escapement

$$S_\beta = \mathbb{S}_\beta(R_\beta).$$

Subsequently this β-escapement spawns, and the offspring grow, then migrate back to the high seas to form the subsequent season's α-fleet recruitment:

$$R_\alpha^+ = F(S_\beta).$$

The process then repeats. Thus, schematically,

$$R_\alpha \longrightarrow S_\alpha = R_\beta \longrightarrow S_\beta \longrightarrow F(S_\beta) = R_\alpha^+ \longrightarrow S_\alpha^+ = R_\beta^+ \longrightarrow \cdots,$$

with both fleets remaining engaged in the harvest for an indefinite period of time.

We shall derive a (perfect) Nash equilibrium for this infinite time-horizon harvesting game. Here the distant water α-fleet adopts an $(\widehat{S}_\alpha, \widehat{R}_\alpha)$-policy:

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

where

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

while the regional β-fleet adopts a policy of most-rapid approach to a target escapement $\widehat{S}_\beta$:

$$S_\beta = \mathbb{S}_\beta(R_\beta; \widehat{S}_\beta) = \min[R_\beta, \widehat{S}_\beta],$$

where

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

(Such an infinite horizon policy profile seems very natural. In fact, it can be obtained as the limit of equilibrium profiles of the same type for finite horizon games, each of which is solvable by backward induction. Here we omit the proof.)

In the competition, the α-fleet will face an *effective stock-recruitment relation*

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

More generally, across n periods

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

Similarly, in the presence of the competing α-fleet, the regional β-fleet faces the *effective stock-recruitment relation* $S_\beta \longrightarrow R^+_\beta = G_\beta[S_\beta]$:

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

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

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

As it turns out, the outcome of the competition 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,

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: $F^{[N-1]}(\widehat{S}_\alpha) < \widehat{R}_\alpha \leq F^{[N]}(\widehat{S}_\alpha) \leq F(S^0_\beta)$

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

$$F^{[N-1]}(\widehat{S}_\alpha) \leq \widehat{S}_\beta. \tag{7}$$

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.

Note that the β-fleet would not optimally forego harvesting during the steady-state cycling if it were able to enter, so that necessarily

$$\widehat{S}_\beta = S^o_\beta.$$

Furthermore the β-fleet can enter initially only if $R_\beta(0) > S^o_\beta$,and then its payoff will be

$$U(R_\beta) = \int_{S^o_\beta}^{R_\beta} \pi_\beta.$$

Iterating the steady-state pattern, it follows (as for an *unopposed* α-fleet) that, for any $R_\alpha > \widehat{R}_\alpha$, $U_\alpha[R_\alpha]$ is given by equation (3). As in that case, the optimal choice of target escapement may be found by differentiating this expression for $U_\alpha[R_\alpha]$ 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, from (7), that

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

Thus optimally

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

where S^{*N}_α is, as before, the target escapement for the unopposed α-fleet.

Finally, arguing as for the sole operator,

$$\widehat{R}_\alpha \triangleq R^{\#N}_\alpha(\kappa^\#)$$

is a monotone increasing function of $\kappa^\#$ on the interval given by (6), with $R^{\#N}_\alpha(\kappa^\#)$ itself given implicitly by equation (5).

As a special case, when

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

then the policy profile

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

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

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

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

If

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

then also

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

and

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

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,

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

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

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

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

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

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

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

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

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

Hence

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

and, under the constraints that

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

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

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

and if κ^o is given by (5) with $\widehat{S}_\alpha = S^o_\alpha$ and $\widehat{R}_\alpha = R^o_\alpha$, then the policy profile

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

will provide the unique period N coexistent Nash equilibrium of target/threshold type corresponding to the fixed cost κ^o.

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

Suppose that

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

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 sole-operator level) and subsequent recruitments $R_\beta = F(\widehat{S}_\beta)$.

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

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

Consider the expression for $U_\beta(R_\beta)$ in equation (3), specialized to N=1. Making explicit the dependence of upon $\widehat{S}_\beta$, and differentiating 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

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

constitutes a Nash equilibrium. As usual $R^o_\alpha(\kappa^o)$ is given implicitly by equation (5), over the range of κ^o given by (6).

CONCLUSIONS

The model analyzed here provides an initial perspective on the high seas confrontation between a regionally-based fishing fleet and a distant-water fleet. Explicitly it models the case where the distant-water fleet's fixed-cost disadvantage is offset by its assumed first-mover's advantage in each season's harvest. The latter we have justified by an assumption that the entire fish stock, after spawning in the EEZs, migrates to international waters, but that the regional fleet decides to confine its harvest to its EEZs. This idealized assumption does seem to approximate reality for a number of major straddling stock fisheries, and the projected results are not inconsistent with what has been observed.

Under these circumstances, the model's projections for competition are consistent with the classical understanding that an unopposed distant-water harvester will engage in pulse fishing, and under stable conditions will return periodically to fish-down the recovering stock. The present model predicts this same behavior even in the presence of a regionally-based competitor. What is different in the competitive situation is that the period between returns will be extended and the stock levels will be depressed even more severely than when only a single unopposed fleet is involved. In extreme cases, depending on the relative competitive strengths of the fleets, one or the other may be completely excluded from the fishery, but exclusion will be achieved by the victor only by depressing the stock. In the more likely situation of relative parity, resulting in fleet coexistence in the fishery, the stock depletion will be still greater. These features may all be regarded as manifestations of the well-known "tragedy of the commons", the result of competitors harvesting from a common pool.

There is a certain irony in these results, for they suggest that the creation of the EEZs has not solved the problem of divided management in marine fisheries, but may actually have exacerbated the problem in many parts of the world.

The results of the present model depend importantly on our assumption that the DWF retains a long term interest in the particular fishery, and can be expected to return repeatedly to harvest as the stock recovers. This perspective is enshrined in the model's assigned objective function for the DWF–namely as a discounted sum of net annual returns over an infinite time horizon.

It is the long-term interest of the DWF that makes it interesting in the analysis of the "new member problem". A non-member state with an active DWF may very likely express an interest in joining the RFMO. However it will wish to enter, if at all, only on highly 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 have not undertaken here to model the bargaining game that might resolve the confrontation. Our purpose at present is only to clarify the negative aspects of a continuing contest, in which the parties both strive to demonstrate their competitive strengths. In a general way, the negative effects are well-known, deriving fundamentally from the fact that harvesters are exploiting a common biological stock pool. The role of our analysis is to describe in some detail how this effect is played out.

The predictions of this particular model are not the last words on the matter. The outcome we have described depends very much on assuming that the two fleets meet on a relatively level "playing field". But in fact the competition will not often be a contest between equals. There are sometimes circumstances present which may strongly favor the incumbent regionally-based coalition. It seems plausible that the incumbent fleet may then be able to exploit these asymmetries strategically, and turn them to competitive advantage.

One possibility that we have explored is that the regionally-based fleet might react more aggressively to the threat posed by the distant water invader, for example by moving a portion of its own harvest to international waters and using its EEZ refugia strategically to protect the fish stock (see McKelvey et. al, [1999]).

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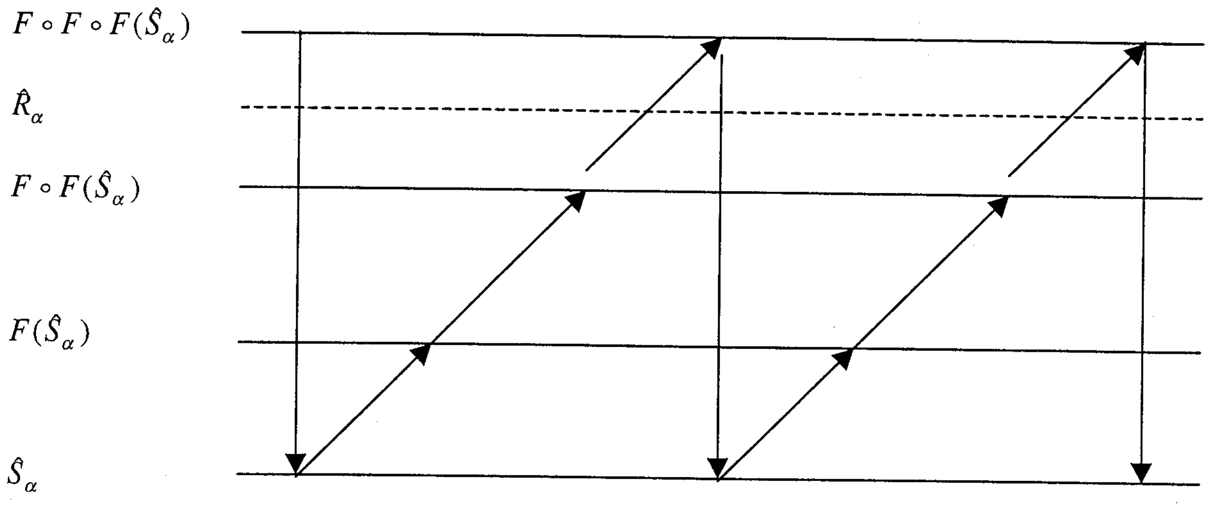

Figure 1.
Monopolistic harvesting. The case of $N = 3$.

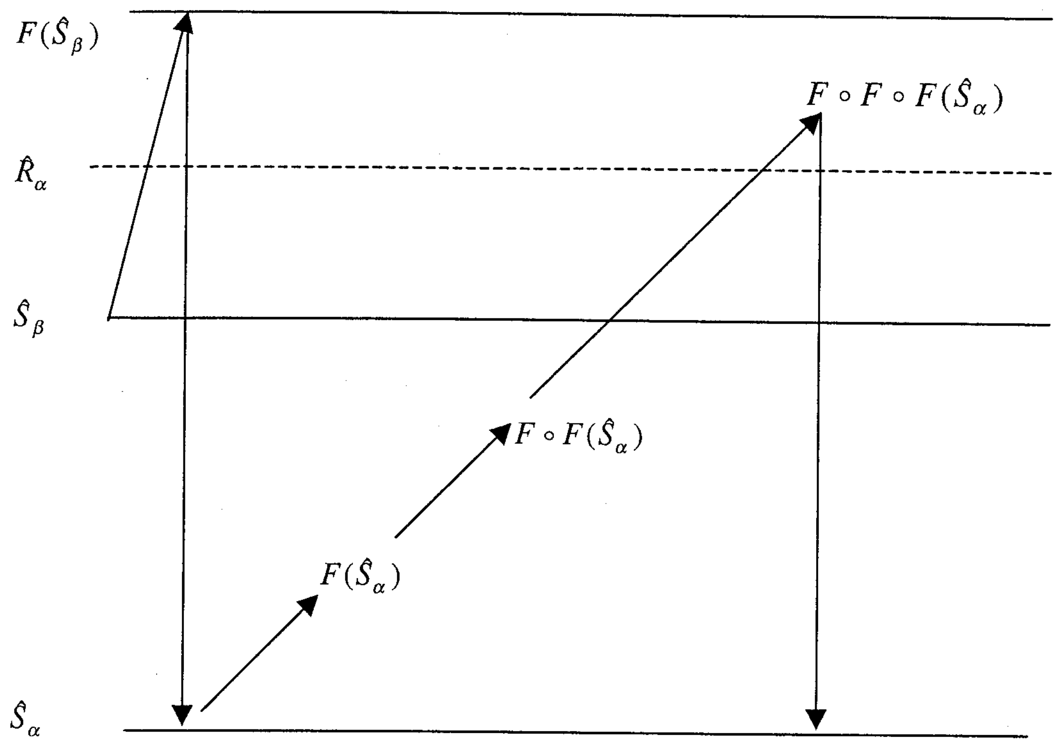

Figure 2. The repeating pulse cycle in the case with α-fleet dominance. $N = 3$.

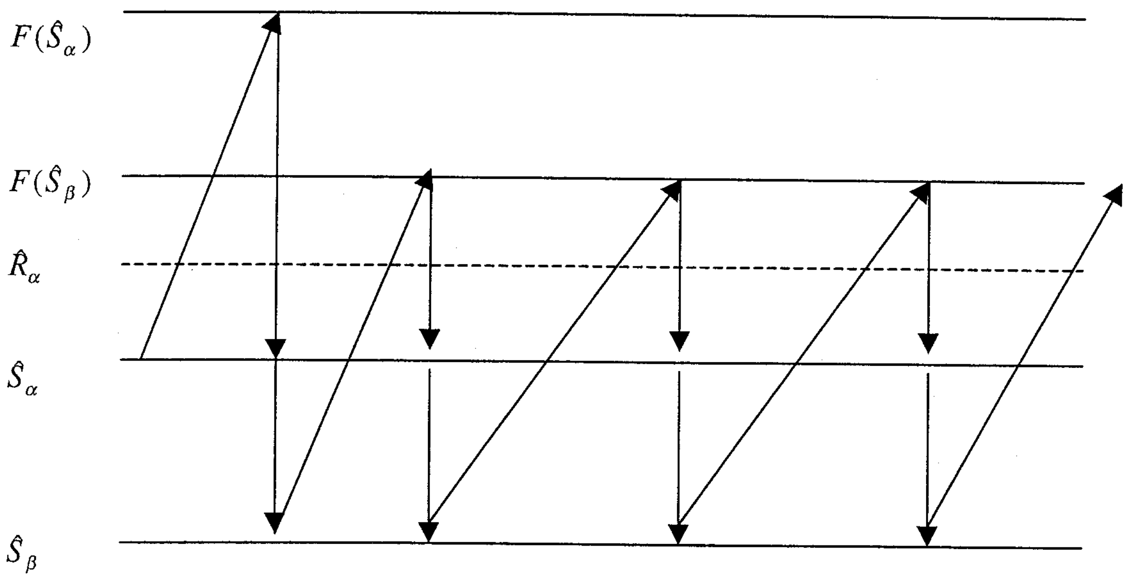

Figure 3. The repeating pulse cycle in the coexistence case for $N = 1$.

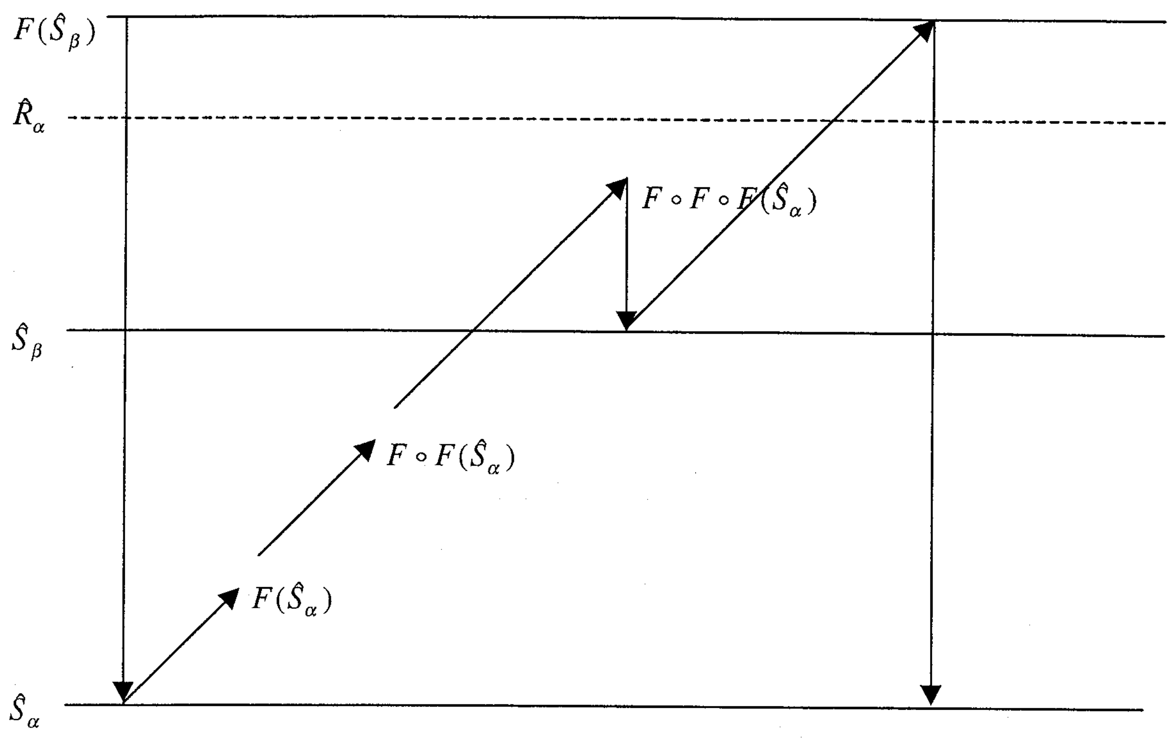

Figure 4. The repeating pulse cycle in the coexistence case. $N = 4$.

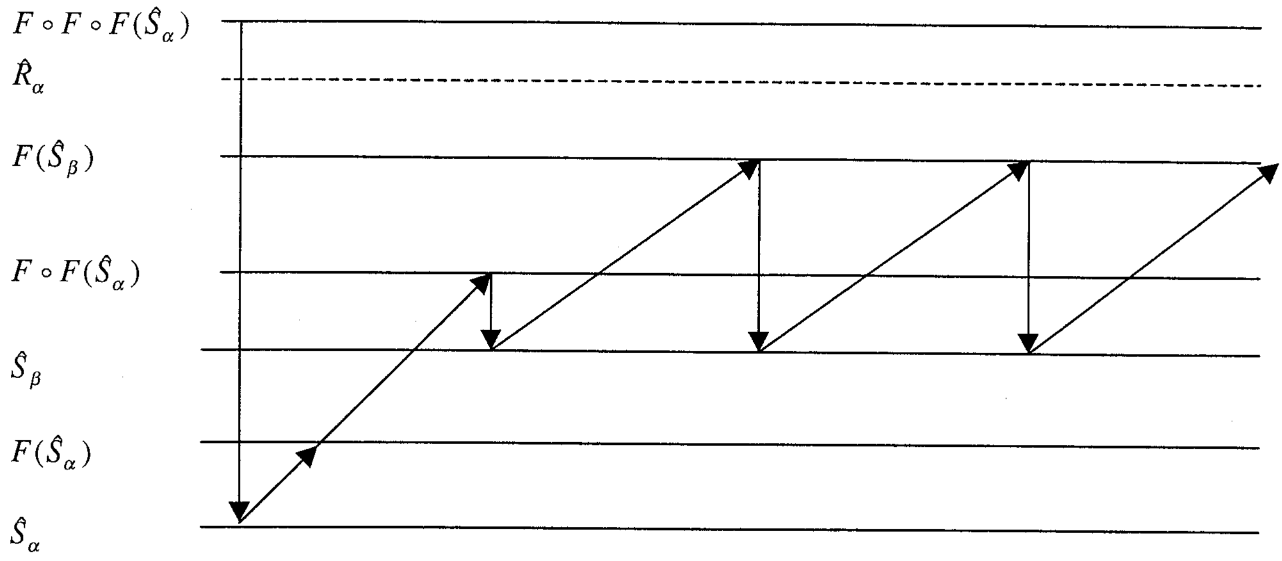

Figure 5.
The repeating single-period pulse cycle in the case with β-fleet dominance.