A Hit-and-Run Interloper Model for a Regional Fisheries Management on the High Sea

LEIF K.SANDAL — *NHH*

STEIN I. STEINSHAMN — *SNF*

ROBERT W. McKELVEY

University of Montana, USA

30. juli 2002

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.

1. 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 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 (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.

However, the agreement provides to the RFMO no coercive enforcement powers,

[1]BASIC SUPPORT FOR ROBERT MCKELVEY'S RESEARCH ON HIGH SEAS MARINE FISHERIES MANAGEMENT HAS BEEN THROUGH GRANT DBI-9708475 FROM THE US NATIONAL SCIENCE FOUNDATION. LEIF SANDAL AND STEIN STEINSHAMN WAS FUNDED BY THE NORWEGIAN RESEARCH COUNCIL. THIS MODELING ANALYSIS WAS DONE DURING SEVERAL VISITS BY PROF. MCKELVEY TO THE NORWEGIAN SCHOOL OF ECONOMICS AND BUSINESS ADMINISTRATION.

either to exclude non-member harvest nor 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. Two inter-related 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. These include individually operated vessels (perhaps flying flags-of-convenience) but also include coordinated multi-vessel "distant water fleets" (DWFs) 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 Kaitala and Munro (1993), as the "new member problem", concerns the inherent difficulties of negotiating, in a timely manner, mutually acceptable terms of entry, which will specify the petitioning nation's membership rights and obligations.

These two separate problems merge when a DWF, previously not heavily engaged in a particular straddling stock fishery, appears on the scene and declares an interest in joining an already well-established RFMO. In this situation the interests of the current members and the applicant are strongly opposed, with current members facing the likelihood of having to give up a portion of their present quotas to the prospective new member, and the applicant believing that it might be advantageous to remain outside of the coalition, continuing to harvest profitably while demonstrating its strategic strengths for future negotiations.

This is the second of two studies, in which we address these inter-related problems. In the first (McKelvey, et. al., 2002) we examine strategic aspects of a confrontation between a RFMO and a DWF, in a situation where the entire stock is susceptible to

DWF high seas harvest. In this case a RFMO, lacking statutory enforcement powers, has little ability through harvest policy alone to mount an effective defense against DWF pulse fishing, and its consequent economic disruption and stock degradation.

Here we examine a straddling stock fishery, when the fish stock range includes a high seas component, but a substantial portion of the stock remains within the exclusive EEZs of the RFMO members, where it is protected against harvest by any DWF fleet. This is a common situation for many major fish stocks worldwide (Meltzer, 1994). The typical behavior of the RFMO states is to confine their harvest to home waters, essentially abandoning the high seas portion of the stock range to the DWFs. In this case, the home fleets can respond to the presence of the high seas DWF by harvesting more intensively on home ground, lowering seasonal escapement and hence the subsequent fishing season's recruitment, and so lowering the likelihood of future entry of the DWF.

But a still more active RFMO strategy might also be contemplated. In an effort to deter the current-season entry of any potential distant-water invader, the regional fleet might move preemptively into international waters, to fish-down the migratory portion of stock. The effect of this high seas overharvest could then be mitigated by a compensating reduction in the scale of the subsequent harvest in the EEZs.

The possibility of success of such aggressive RFMO strategies rests on the assumed likelihood that a DWF will face higher fixed costs of high seas entry than will the regional fleet. Not only are there the transportation costs of moving a DWF fleet to a distant fishing ground and maintaining it there, but there are also opportunity costs of doing so: A DWF fleet, displaced from its more traditional harvest grounds and seeking out targets-of-opportunity on the high seas, will have several options to choose from, and will enter this particular fishery only if the reward for doing so exceeds the potential return from harvesting elsewhere. Aggressive high seas harvesting by the

RFMO may tip the balance decisively against DWF entry.

In this study we undertake to determine the optimal harvest policy for the RFMO β-fleet, *given that it is undertaking total α-fleet (DWF) exclusion.* Such a policy may often be expensive to implement but might be justified as avoiding potentially far more costly damage to the stocks from the distant-water harvesting and also as a means of establishing a reputation for aggressiveness in any future confrontations. It is most likely to prove effective when the distant-water fleet faces high entry costs and/or the migratory fraction of the fish-stock is small.

The existing game-theoretic analysis of industrial organization, (e.g. Tirole, 1988), provides some helpful insights into economic entry barriers, 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 common-property externality reduces the effectiveness of any potential economic barrier which operates exclusively within the fishery sector.

2. THE BASIC FISHERY MODEL

We shall consider the case of a single harvested fish stock with non-overlapping generations, a stock which spawns in nursery grounds that lie entirely within the EEZs of the RFMO countries. Following dispersal, the young eventually mature to a harvestable stock biomass R, called the "recruitment to the fishery". This recruitment divides into two parts. One fraction $R_\theta = \theta R$ will migrate beyond the territorial waters, into adjacent areas of the high seas, where it potentially is subject to harvest by both a distant-water α-fleet and the RFMO β-fleet. The remaining fraction

$$R_\phi = \phi R \text{ , } (1 - \theta)R$$

remains within the territorial EEZs. We assume that high seas harvest occurs first, ahead of harvest within the EEZs, and that thereby the high seas stock is reduced to a high seas "escapement" S_θ. . This residual high seas stock then returns to the EEZs where it merges with the unharvested resident substock R_ϕ to form a final seasonal harvestable stock

$$R_\beta = R_\phi + S_\theta,$$

accessible only to the regional fleet. A home-waters harvest, by the regional fleet, now reduces R_β to the end-of-season escapement biomass S_β, which returns to the nursery ground to spawn and die.

The offspring generation from the spawn then matures to form, at the beginning of a new harvest season, a new recruitment level R^+. The cycle then repeats. The offspring recruitment R^+ is determined from its parental biomass S_β by the (deterministic) stock-recruitment equation.

$$R^+ = F(S_\beta).$$

Here $F(S_\beta)$ is monotone increasing and concave, with

$$F(0) = 0$$

and a single positive fixed point K (the "carrying capacity"), where

$$F(K) = K.$$

Schematically,

$$\begin{array}{cccccccccccc}
 & & & (h_\alpha + h_{\beta\theta}) & & & & & & & & \\
 & & R_\theta = \theta R & \longrightarrow & S_\theta & & & & & & & \\
 & \nearrow & & & & \searrow & & (h_{\beta\phi}) & & & & \\
R & \longrightarrow & R_\phi = \phi R & \longrightarrow & \longrightarrow & \longrightarrow & R_\beta & \longrightarrow & S_\beta & \longrightarrow & R^+ = F(S_\beta) &
\end{array}$$

2.1 Centrally-Managed Harvesting: A Baseline Model.

As a baseline to consideration of this competitive harvest, first assume RFMO central management of the fishery, where there is no threat of entry by an outside DWF. Thus all harvesting, $h_{\beta\phi}$ in EEZs and $h_\theta = h_{\beta\theta}$ on the high seas, is conducted exclusively by the RFMO fleet.

The β-fleet's annual payoff from its harvests, on high-seas and in home waters, will be

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

Here, π_θ and π_β may be any monotone increasing functions. A frequent choice is $\pi_\theta(x) = p - c_\theta/x$ and $\pi_\beta(y) = p - c_\beta/y$.

The home fleet's objective is to choose its harvest policy to maximize the discounted sum of future annual returns.

$$\sum_{t=0}^{\infty} \gamma^t \Pi_\beta(t),$$

with given discount factor $\gamma < 1$. We shall make the simplifying assumption (quite often bourn out) that home-ground harvest costs are lower than those on the high seas (for example, $c_\beta < c_\theta$). This implies that *when there is no threat of invasion* the home fleet will harvest exclusively in home waters. In fact, for any assumed total annual harvest, seasonal value $\Pi_\beta(t)$ will be greatest when all harvest is postponed until the high seas stock has returned to the EEZs.

The cyclic generational pattern now simplifies to:

$$\begin{array}{ccccccccc} & & R_\theta & & & & & & \\ & \nearrow & & \searrow & h_{\beta\phi} & & & & \\ R & \longrightarrow & R_\phi & \longrightarrow & R & \longrightarrow & S_\beta = R - h_{\beta\phi} & \longrightarrow & R^+ = F(S_\beta). \end{array}$$

It follows from standard harvesting theory [e.g. Clark, 1990] that a centrally managed fleet, when harvesting monopolistically on home ground and maximizing the objective function

$$\sum_{t=0}^{\infty} \gamma^t \int_{S_\beta(t)}^{R(t)} \pi_\beta(y)dy,$$

will set a harvest policy of fishing-down to a fixed target escapement S_β^* :

$$S_\beta(t) = \begin{cases} S_\beta^* & \text{if } S_\beta^* \leq R(t) \\ R(t) & \text{otherwise.} \end{cases}$$

The target S_β^* will be chosen optimally according to the usual marginal rule that

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

with

$$R^* = F(S_\beta^*).$$

We shall assume that $S_\beta^0 < S_\beta^* < K$, where S_β^0 is the bionomic stock level at which $\pi_\beta(S_\beta^0) = 0$. Hence the triple

$$(S_\theta^* = \theta R^*, \quad S_\beta^*, \quad R^*)$$

defines a steady-state pattern, with

$$S_\beta^0 < S_\beta^* < R^* < K,$$

and the cycle

$$R^* \longrightarrow S_\beta^* \longrightarrow R^* = F(S_\beta^*)$$

repeating endlessly.

3. COMPETITIVE HARVEST

Next we return to consideration of a harvesting confrontation, between a distant-water α-fleet (DWF) and the combined β-fleet of the RFMO countries. As described above, the β-fleet can harvest in its combined territorial waters (its EEZs) but also on the high seas. The distant water α-fleet's harvest is confined to the high-seas region.

For simplicity we assume that, in a season when both fleets undertake a high seas harvest, the β-fleet's high seas harvest will *precede* the harvest by the distant-water α-fleet. Other assumptions would yield similar results. If the β-fleet does enter, it will harvest a biomass $h_{\theta\beta} \geq 0$, reducing the high seas recruitment R_θ to an escapement

$$S_{\theta\beta} = R_\theta - h_{\theta\beta}$$

A subsequent α-fleet harvest $h_\alpha \geq 0$ drops the high seas escapement still further, to

$$S_\theta = S_{\theta\beta} - h_\alpha = R_\theta - (h_{\theta\beta} + h_\alpha).$$

The cyclic generational pattern is thus elaborated to

$$\begin{array}{ccccccccccccc}
 & & & (h_{\theta\beta}) & & (h_\alpha) & & & & & & & \\
 & & R_\theta & \longrightarrow & S_{\theta\beta} & \longrightarrow & S_\theta & & & & & & \\
 & \nearrow & & & & & & \searrow & & (h_{\phi\beta}) & & & \\
R & \longrightarrow & R_\phi & \longrightarrow & \longrightarrow & \longrightarrow & \longrightarrow & \longrightarrow & R_\beta & \longrightarrow & S_\beta & \longrightarrow & R^+ = F(S_\beta)
\end{array}$$

Unlike the home-based β-fleet, the distant-water α-fleet can be expected to experience a significant fixed cost of entry, both in transportation costs in moving the fleet and in opportunity costs of passing over alternative harvesting opportunities. Accordingly we assume that *the α-fleet's policy is to enter the high seas fishery only if $S_{\theta\beta}$*

exceeds a critical threshold level R_α, which may lie well above its target escapement level (compare McKelvey et al., 2002).

In this study we undertake to determine the optimal harvest policy for the RFMO β-fleet, *given that it is undertaking total* α*-fleet exclusion.* We assume that indeed the β-fleet has the effort capacity necessary to exclude α-fleet entry completely, thus

$$S_\theta = S_{\theta\beta} \leq R_\alpha,$$

though such exclusion may come only at high cost. The rationale for, and implications of, this assumption will be explored in the concluding section of the article.

The *optimal* β-fleet policy for achieving α-exclusion *in any particular season* depends, first of all, on the initial recruitment R at the beginning of that season. Because of our continuing assumption, of lower β-fleet harvesting costs in home waters than on high seas, therefore *optimally,* $S_{\theta\beta} \leq R_\alpha$ *should be achieved with minimal high-seas* β*-fleet harvest.* Thus, in any harvest season with initial recruitment R, the high seas β-fleet escapement must be

$$S_\theta = S_{\theta\beta} = \min[\theta R, R_\alpha].$$

That is, β-fleet high seas harvest occurs only when necessary to bring the high seas stock down to the α-fleet's entry threshold. Otherwise β-fleet harvesting is confined to its home waters. Equivalently, in any harvest season S_θ is determined by the size of recruitment R relative to a *critical recruitment level*

$$R^{crit} \;,\; R_\alpha/\theta.$$

Specifically,

$$S_\theta = S_{_{\theta\beta}} = \begin{cases} R_{\alpha,} & \text{if } R^{crit} \leq R; \\ \theta R, & \text{if } R \leq R^{crit}. \end{cases}$$

3.1 Feasible Escapements and Feasible Steady-States

While S_θ is completely determined in this way, the corresponding home-waters escapement level S_β is only constrained, by the obvious *feasibility constraint* that home waters escapement cannot exceed home waters final recruitment R_β. Thus, *for given recruitment* R,

$$S_\beta \leq R_\beta = S_\theta + R_\phi = \min[R, R_\alpha + \phi R] = \min[R, \theta R^{crit} + \phi R].$$

More explicitly,

$$S_\beta \leq R_\alpha + \phi R \quad \text{if } R^{crit} \leq R;$$

or

$$S_\beta \leq R \quad \text{if } R \leq R^{crit}.$$

In particular, in order for a given escapement $\widehat{S}_\beta \leq K$ to generate a *feasible steady-state* cycle

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

the above feasibility constraint becomes that

$$\widehat{S}_\beta \leq \min[F(\widehat{S}_\beta), R_\alpha + \phi F(\widehat{S}_\beta)].$$

Note that, if $\widehat{R} \leq R^{crit}$, the steady-state feasibility requirement says only that $\widehat{S}_\beta \leq \widehat{R} = F(\widehat{S}_\beta)$, and this follows automatically from the assumption ($\widehat{S}_\beta \leq K$) that $\widehat{S}_\beta$ generates a steady state.

In the opposite case where

$$R^{crit} < \widehat{R} < K,$$

the steady-state feasibility constraint

$$\widehat{S}_\beta \leq R_\alpha + \phi \widehat{R}$$

may be written as

$$F^{-1}(\widehat{R}) \leq R_\alpha + \phi\widehat{R}$$

or as

$$R_\alpha \geq G(\widehat{R}, \phi) \;,\; F^{(-1)}(\widehat{R}) - \phi\widehat{R}.$$

In figure 1, the convex graph of $\widehat{S}_\beta = F^{(-1)}(\widehat{R})$ and the straight line graphs of $\widehat{R}$ and $\phi\widehat{R}$ are plotted against $\widehat{R} \in [0, K]$, for fixed values of the parameters (R_α, θ). For any choice of steady-state recruitment $\widehat{R} \leq K$, the total harvest is the vertical interval from the graph of $\widehat{R}$ down to the escapement $\widehat{S}_\beta$, with the high-seas portion of the harvest lying above the boldface graph of $\widehat{R}_\beta = \min[\widehat{R}, R_\alpha + \phi\widehat{R}]$.

The figure shows too that there is a steady-state recruitment level $R_o \geq 0$ such that for any $\widehat{R} \leq R_o$ the graph of $\widehat{S}_\beta$ lies below that of $\phi\widehat{R}$. Thus for $\widehat{R} < R_o$ the initial home-ground recruitment $\phi\widehat{R}$ alone is adequate to assure that the steady-state feasibility constraint will be met. But for $\widehat{R}$ on the interval (R_o, K), the graph of $\widehat{S}_\beta$ is above that of $\phi\widehat{R}$, so that satisfying steady-state feasibility will require also some high-seas harvest. Note that on that interval, the vertical separation $G(\widehat{R}, \phi)$ between these two graphs is monotone-increasing in $\widehat{R}$, taking on all positive values between 0 at R_o and θK at $R = K$.

Hence there is a *unique* feasible steady-state recruitment level $\widehat{R} = \widetilde{R}(R^{crit}, \phi) \in [R_o, K)$ for which

$$G(\widetilde{R}, \phi) = R_\alpha.$$

This is precisely the recruitment level $\widetilde{R} > R^{crit}$ where the steady-state feasibility constraint binds. Consequently this particular recruitment generates the feasible steady-state configuration

$$\widehat{S}_\theta = \theta\widetilde{R}, \quad \widehat{S}_\beta = \widetilde{S}_\beta = F^{-1}(\widetilde{R}), \quad \widehat{R} = \widetilde{R}$$

which entails *only* a high seas harvest.

As figure 1 illustrates, each recruitment level $\widehat{R}$ on the interval

$$0 < \widehat{R} \leq \widetilde{R}$$

meets the steady-state feasibility requirement, with the high-seas harvest pinching out at $\widehat{R} = R^{crit}$. But no steady-state recruitment level $\widehat{R}$ on

$$\widetilde{R} < \widehat{R} \leq K$$

is feasible, since there $R_\alpha < G(\widehat{R}, \phi)$.

3.2 Optimal defensive management by the β-fleet.

We turn now to an examination of which, among the feasible steady-states, will in fact be optimal as a target, for maximizing the β-fleet's discounted-sum payoff while deterring the entry of the α-fleet. The answer will depend on the particular values of the parameter pair (R_α, θ)

We shall focus on the situation of a RFMO's β-fleet which, up to the present time, had been harvesting optimally at steady-state S^*_β without external challenge. But, we assume, from this time onward it is faced with a constant threat of entry by a distant-water α-fleet, with entry threshold R_α. Thus to exclude α-fleet entry the β-fleet must initially harvest-down the high seas recruitment θR to R_α, then follow up by an optimal sequence of subsequent home waters and high seas harvests, always keeping $S_{\beta\theta} \leq R_\alpha$. The way in which this is accomplished depends on the relative size of the entry-threshold level R_α of the α-fleet, as compared to the high-seas recruitment θR^* which prevails when the β-fleet harvests optimally as an unchallenged sole-operator.

The resolution is particularly easy when the challenging fleet has an especially high entry threshold: i.e. when $R_\alpha \geq \theta R^*$. Recalling that, by assumption, $R^* < K$, this implies that $S^*_\beta \leq R^* \leq R^{crit}$. In this case the incumbent fleet need only modify its sole-operator optimal policy mildly, by setting

$$S_\theta = \min[R_\alpha, \theta R],$$

in order to deter α-fleet entry. Note that, for initial $R \geq S_\beta^*$, one has

$$R_\beta = \min[\theta R^{crit} + \phi R, R] \geq S_\beta^*,$$

while if initial $R \leq S_\beta^*$ then

$$R_\beta = R.$$

Hence set

$$S_\beta = \min[R_\beta, S_\beta^*] = \left\{ \begin{array}{l} S_\beta^* \ \text{ if } R_\beta \geq S_\beta^* \\ R \ \text{ if } R_\beta \leq S_\beta^* \end{array} \right| .$$

Thus this modified sole-operator policy continues to lead to yield a trajectory of most-rapid-approach to the optimal sole-operator steady-state, while simultaneously deterring α-fleet entry.

Thus, in what follows, we can concentrate on the situation where

$$R_\alpha < \theta R^*.$$

with entry threshold low relative to the unchallenged home fleet's steady-state recruitment.

3.3 Determining Admissible Steady-States

In general the β-fleet's *optimal* competitive harvest escapement S_β, given the entry threshold R_α of the α-fleet and the current recruitment R, is determined by solving a dynamic programming equation. Let $V[R]$ denote the optimal (discounted sum) payoff to the β-fleet Assuming a positive harvest in the initial year, so that $R > S_\beta$.the dynamic programming equation (DPE) is

$$V[R] = \begin{cases} \int_{R_\alpha}^{\theta R} \pi_\theta(s)ds + \max_{S_\beta \le R_\alpha + \phi R} \left\{ \int_{S_\beta}^{R_\alpha+\phi R} \pi_\beta(s)ds + \gamma V[F(S_\beta)] \right\} & \text{if } R^{crit} < R; \\ \max_{S_\beta \le R} \left\{ \int_{S_\beta}^{R} \pi_\beta(s)ds + \gamma V[F(S_\beta)] \right\} & \text{if } \; R \le R^{crit}. \end{cases}.$$

Note that the permissible range of S_β is determined by the feasibility constraint, that home-waters escapement S_β cannot exceed terminal home-waters recruitment R_β. In particular, if $R \le K$, then the corresponding steady-state escapement $S_\beta = F^{-1}(R)$ lies within the feasible range.

Our goal is to determine the feasible escapement

$$S_\beta = S_\beta(R; R_\alpha, \theta)$$

which maximizes $V[R]$ for large R. In this section we narrow down the candidate set of escapements to those which provide *local extrema* of $V[R]$, within the permissible range of feasibility. To find an interior extremum, one differentiates the bracketed expression in the DPE by S_β. Each *locally-optimal* escapement necessarily must satisfy

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

with the inequality possible only when the feasibility constraint binds. Here

$$\lambda(R) \text{ , } \frac{d}{dR}V(R). = \begin{cases} \pi_{mix}(R, R_\alpha, \theta) & \text{if } R > R^{crit}; \\ \pi_\beta(R) & \text{if } R \le R^{crit}. \end{cases}.$$

where

$$\pi_{mix}(R, R_\alpha, \theta) \text{ , } \theta\pi_\theta(\theta R) + \phi\pi_\beta(R_\alpha + \phi R).$$

In particular when the feasibility constraint

$$S_\beta \le \min[R, R_\alpha + \phi R]$$

does not bind, which is so *if R is sufficiently large,* then S_β generates a feasible steady-state which satisfies

$$\pi_\beta(S_\beta) = \gamma F'(S_\beta) \begin{cases} \pi_{mix}[F(S_\beta), R_\alpha, \theta] & \text{if } F(S_\beta) \geq R^{crit}; \\ \pi_\beta[F(S_\beta)] & \text{if } F(S_\beta) \leq R^{crit}. \end{cases} .$$

independent of large R.

As discussed previously, the global solution to the equation

$$\pi_\beta(\widehat{S}_\beta) = \gamma F'(\widehat{S}_\beta)\pi_\beta[F(\widehat{S}_\beta)]$$

is $\widehat{S}_\beta = S^*_\beta$.

However the equation

$$\pi_\beta(S^\#_\beta) = \gamma F'(S^\#_\beta)\pi_{mix}[F(S^\#_\beta), R_\alpha, \theta]$$

for a given parameter pair (R_α, θ), may have one or more formal solutions, or none at all. Any formal solution interior to the interval

$$S^{crit}_\beta \leq S^\#_\beta \leq \widetilde{S}_\beta,$$

with $F(S^{crit}_\beta) = R^{crit}$, generates a steady-state with β-fleet harvest both on high-seas and in home-waters. A solution coinciding with an endpoint of this interval generates a steady-state with harvest at just one of these sites. On the other hand, $S^\#_\beta$ lying outside of this interval either fails to be feasible (when $\widetilde{S}_\beta < S^\#_\beta$) or is not locally optimal (when $S^\#_\beta < S^{crit}_\beta$).

The defining equation for $S^\#_\beta$ represents a new *marginal rule,* analogous to that which is satisfied by S^*. It equates the immediate return, from harvest of the marginal unit of the fish stock at the two sites, to its potential value from maintaining it in the brood stock to enhance subsequent recruitment.

Along with S^*_β, the steady-state escapements S^{crit}_β, $\widetilde{S}_\beta$, and $S^\#_\beta \in [S^{crit}_\beta,\ \widetilde{S}_\beta]$ will be termed *admissible steady-state escapements:* the true optimal escapement for $R_\alpha > \theta R$ will necessarily take on one of these values. Of course if $R_\alpha \geq \theta R^*$ (i.e. if $R^{crit} \geq R^*$), then S^*_β already has been established to be the optimum escapement.

Thus it remains to determine the global optimum when $R_\alpha < \theta R^*$ (i.e. when $R^{crit} < R^*$).

3.4 Determining the optimal admissable steady-state.

The discounted-sum payoff, starting from a sufficiently large fixed initial recruitment R and resolving directly into a pattern of steady-state harvests on both high seas and home waters, is

$$W[R, S_\beta] = \int_{R_\alpha}^{\theta R} \pi_\theta + \int_{S_\beta}^{R_\alpha + \phi R} \pi_\beta + \frac{\gamma}{1-\gamma}\left[\int_{R_\alpha}^{\theta F[S_\beta]} \pi_\theta + \int_{S_\beta}^{R_\alpha + \phi F[S_\beta]} \pi_\beta\right].$$

This pattern is feasible for any S_β such that $S^{crit} < S_\beta < \widetilde{S}_\beta$, and in particular for any $S^\#_\beta \in [S^{crit}, \widetilde{S}_\beta]$. However the formal expression which defines the payoff is meaningful as a mathematical expression for *any* $S_\beta \leq K$, even though, outside of the region of feasibility, the corresponding triple $[F(S_\beta), R_\alpha, S_\beta]$ will no longer represent an attainable harvesting pattern.

Differentiating W by S_β, one finds

$$(1-\gamma)W'(S_\beta)\ \text{,}\ (1-\gamma)\partial_{S_\beta} W[R, S_\beta;] = -\pi_\beta(S_\beta) + \gamma F'(S_\beta)\cdot\pi_{mix}[F(S_\beta), R_\alpha, \theta],$$

independent of R.

Note that, for fixed $[R_\alpha, \theta]$, one has by the definition of $S^\#_\beta$, that $W'(S^\#_\beta) = 0$ for any and all values of this multi-valued function, but at no other values of S_β. Note also that, when $S_\beta = K$, one has

$$(1-\gamma)W'(K) = -\pi_\beta(K) + \gamma F'(K)\cdot\pi_{mix}[K, R_\alpha, \theta] < -\pi_\beta(K)[1 - \gamma F'(K)] < 0.$$

This result can aid in determining which of the zeroes of the multi-valued function $S_\beta^\#$ are maxima and which are minima. Thus if, for a given $[R_\alpha, \theta]$, this function has only simple zeroes, then $W(S_\beta)$ has a local maximum at the upper branch of $S_\beta^\#$ and alternating local minimum and maxima at subsequent branch.

4. SYNTHESIS OF RESULTS: AN ILLUSTRATION

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 parameter pair (R_α, θ) as follows:

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

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

is optimal, and leads to the stable steady state $\{S_\theta^*, S_\beta^*, R^*\}$, with $R^* = F(S_\beta^*)$ and $S_\theta^* = \theta R^*$. By assumption, $R^* < K$, so that this policy is always optimal when $R^{crit} \geq K$, i.e. when the α-fleet entry threshold is high relative to the high-seas migratory fraction of the stock.

B) Hereafter consider that, for given (R_α, θ),

$$R^{crit}(R_\alpha, \theta) < R^* < K.$$

The globally-optimal steady state will be determined by a steady-state recruitment $\widehat{R}$ on the interval

$$R^{crit} \leq \widehat{R} \leq \widetilde{R},$$

and will occur at one of the local optima of $R^\#$ lying within this closed interval or at one of the endpoints, should it be a (constrained) local maximum. The outcome is unambiguous when there is only one local maximum in the interval. If there are more, then the outcome may depend on the value of the initial recruitment $R(0)$ at time $t = 0$.

There are a number of possibilities, depending on the multiplicity of the multiple-valued function $R^{\#}(R_\alpha, \theta)$. We illustrate by considering the cases that arise in fig. 2 and, and in the panels shown in figure 3. Figure 2 shows the value function, W, against R, and the possibilities that arise below the graph. Figure 3 shows S^*, $S^{\#}$, S^{crit} and $\widetilde{S}$ against R_α for a given θ.

A typical situation is that shown in figure 3 (lower right), where the curve defining $R^{\#}(R_\alpha, \theta)$, regarded as a function of R_α for fixed θ, has no solution for small R_α, is double valued for sufficiently large R_α,and single valued at the boundary between these two intervals of R_α. Furthermore, these formal solution values need not lie within the interval of feasibility $R^{crit} \leq R^{\#} \leq \widetilde{R}$, see figure 2 also. Where there are two, and both are feasible, it turns out that the higher one $\overline{R}^{\#}$ is a maximum and the lower $\underline{R}^{\#}$ a minimum, as shown by the following argument.

B_1) Consider that, for given (R_α, θ), the multi-valued function $R^{\#}(R_\alpha, \theta)$ is empty so that $W'(\widehat{S})$ is never zero, and hence remains negative for all $\widehat{S} \in [S^{crit}, \widetilde{S}]$. Thus the maximum of $W(\widehat{S})$ on that interval occurs at

$$\widehat{S} = S^{crit},$$

and the optimal policy is most-rapid approach to the stable steady state

$$\widehat{S}_\theta = R_\alpha, \quad \widehat{S}_\beta = S_\beta^{crit} = F^{(-1)}(R^{crit}), \qquad \widehat{R} = R^{crit}$$

defined by

$$\widehat{R} = R^{crit}$$

Thus for any seasonal recruitment R,

$$\begin{aligned} S_\theta &= \min[R_\alpha, \theta R]; \text{ and} \\ S_\beta &= \min[S_\beta^{crit}, R]. \end{aligned}$$

This can be seen in all four panels of figure 3.

B_2) Consider now that the function $R^{\#}(R_\alpha, \theta)$ is double-valued, with $\underline{R}^{\#} < \overline{R}^{\#}$, and that.$W'(\widehat{S})$ has simple zeroes at $\underline{S}^{\#}$ and $\overline{S}^{\#}$. Then, since $W'(K) < 0$, it follows that $W(\widehat{S})$ has a global maximum at $\overline{S}^{\#}$ and a global minimum at $\underline{S}^{\#}$. Again there are several possibilities. In fact, there are six possibilities altogether as can be recognized from figure 2.

Case I: If

$$\underline{R}^{\#} < R^{crit} < \overline{R}^{\#} < \widetilde{R},$$

then $R = \overline{R}^{\#}$ is a local maximum and both $R = R^{crit}$ and $R = \widetilde{R}$ are local minima of W on the closed interval $[R^{crit}, \widetilde{R}]$ Hence the two-region harvest policy determined by

$$\widehat{R} = \overline{R}^{\#}$$

is optimal, with

$$\widehat{S}_\theta = R_\alpha, \qquad \widehat{S}_\beta = S_\beta^{crit} = F^{(-1)}(R^{crit}), \qquad \widehat{R} = R^{crit}$$

$$R_{crit}(R_\alpha, \theta) \leq R^{\#}(R_\alpha, \theta),$$

and

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

Case II Suppose

$$\underline{R}^{\#} < \quad \overline{R}^{\#} < R^{crit} < \widetilde{R}$$

or

$$R^{crit} < \widetilde{R} < \underline{R}^{\#} < \quad \overline{R}^{\#}.$$

then, throughout the interval $[R^{crit}, \widetilde{R}]$, one has $W'(\widetilde{S}) < 0$. Hence, as in case B_1, the policy determined by

$$\widehat{R} = R^{crit}$$

is optimal. Thus there is only a home-waters harvest at steady state.

On the other hand, if .

$$\underline{R}^{\#} < R^{crit} < \widetilde{R} < \overline{R}^{\#}$$

then, throughout the interval $[R^{crit}, \widetilde{R}]$, one has $W\prime(\widehat{S}) > 0$. Hence the policy determined by

$$\widehat{R} = \widetilde{R}$$

is optimal. Thus there is only a high seas harvest at steady state.

Finally

Case III Here the optimal policy is ambiguous, and may depend not only on (R_α, θ) but also on the initial recruitment $R(0)$.

In the first subcase, where

$$R^{crit} < \underline{R}^{\#} < \overline{R}^{\#} < \widetilde{R}$$

then

$$\text{both } \widehat{R} = \overline{R}^{\#} \text{ and } \widehat{R} = R^{crit}$$

provide local maxima of $W'(\widehat{S}_\beta)$, and hence each remains a candidate for optimal steady-state recruitment. (However at the parameter value (R_α, θ) where the two branches join (so $\underline{R}^{\#} = \overline{R}^{\#}$), then $W\prime(\widehat{S}_\beta) \leq 0$ throughout $[R^{crit}, \widetilde{R}]$ so that $\widehat{R} = R^{crit}$.)

In the second subcase, where

$$R^{crit} < \underline{R}^{\#} < \widetilde{R} < \overline{R}^{\#}$$

then again there are two local maxima of $W'(\widehat{S}_{\beta})$ within $[R^{crit}, \widetilde{R}]$, so

$$\text{either } \widehat{R} = \widetilde{R} \text{ or } \widehat{R} = R^{crit}.$$

5. CONCLUSIONS

The above analysis is highly idealized, but perhaps suggestive. It shows that, in principle, an aggressive harvesting policy by an incumbent fleet could deter entry by a distant-water fleet, by deliberately drawing down the high-seas stock. It also shows that, depending on the relative strategic strengths of the fleets, this might sometimes be achieved by relatively modest deviations from unchallenged monopolistic policies. The analysis could be elaborated to incorporate greater realism. (For example, a more realistic model formulation would make R_{α} stochastic, and only partially predictable by the β-fleet. In that circumstance, the task before the β-fleet would become to develop a harvest policy which would achieve a balance between ongoing costs of deterrence and the occasional severe disruption of the fishery by interloper fleets.)

However the analysis does demonstrate that the strategies explored here are rather desperate: The economic and ecological losses they entail might be acceptable on a few occasions (to prevent a catastrophic stock draw-down by a one-time potential invader), but an on-going policy of preemptory high-seas stock draw-down could be a very expensive form of insurance against an ongoing threat. Furthermore, it carries its own risks, since fishery stock-assessment is an uncertain science, and mis-calculations (especially leading to over-harvesting) could be quite damaging.

The strategic position of an incumbent β-fleet attempting such a policy could be very weak. Indeed, if the DWF's threshold entry level is below the β-fleet's high-seas break-even level, then exclusion is possible only by harvesting at a loss. Even when high-seas harvesting is profitable, it will be less so than continuing to harvest exclusively at home. And even if exclusion is possible without a high-seas β-harvest, the home-waters target escapements necessary to achieve exclusion will be below the level that would be most profitable for an unchallenged monopolist. As we have seen, for such low levels of the DWF's entry barrier, the home-fleet's policy may be discontinuous, implying sudden drops in the escapement. The picture is somewhat brighter when the distant-water fleet's entrance threshold is high, and/or the fraction of recruitment that is accessible to the invading α-fleet is small.

Still, variants in the strategy might mitigate the costs and risks. 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. Even such a more flexible policy would have its costs: Not only would it require the maintenance of an expensive response capability, but its implementation would require undertaking occasional substantial stock draw-downs, that might be highly detrimental to future stock productivity. And, once again, miscalculations would be likely and could be very expensive. Thus there would remain an incentive to develop a more effective means of deterrence, or to work out a cooperative solution.

In conclusion, 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 can often 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] Clark, Colin W., 1990, *Mathematical bioeconomics: The optimal management of renewable resources* (Wiley, New York).

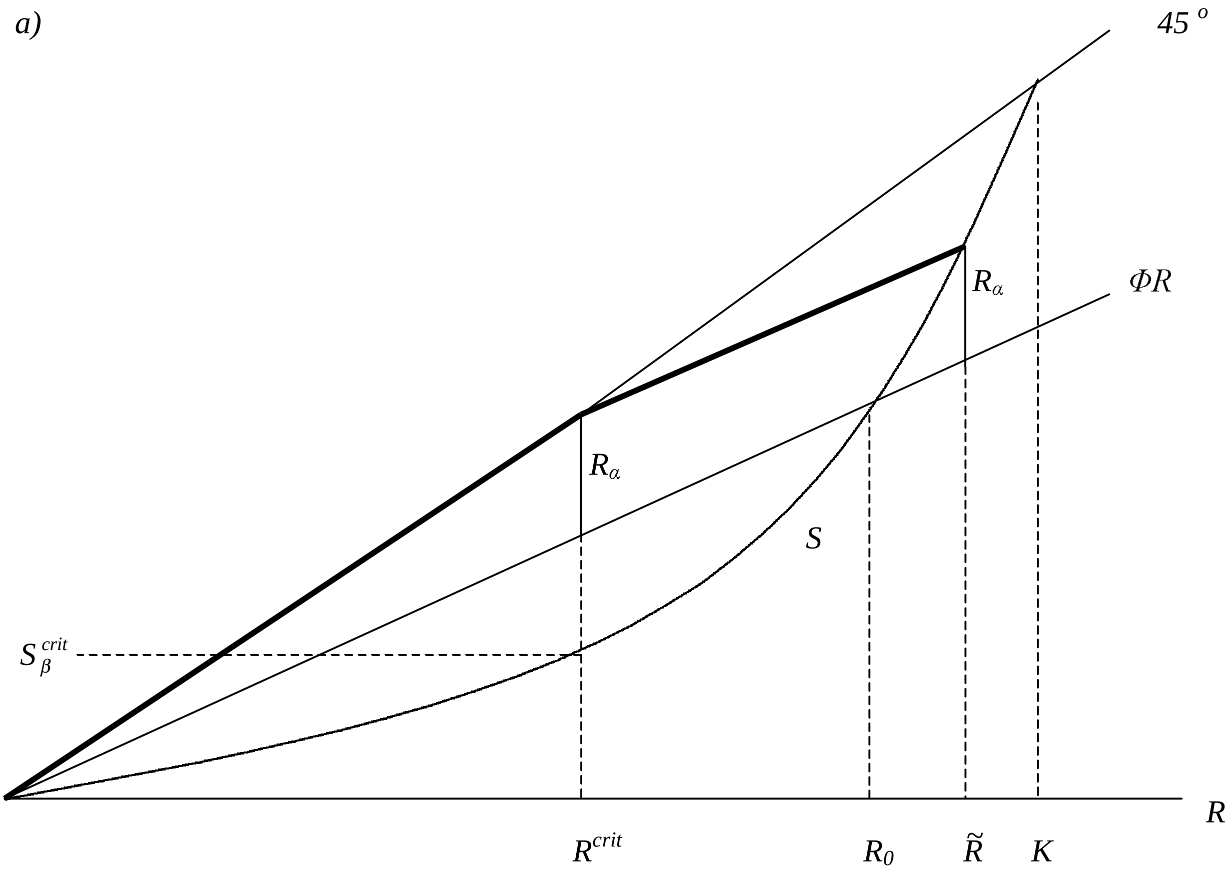
[2] Kaitala, Veijo and Gordon R. Munro, 1993, The management of high seas fisheries, *Marine Resource Economics* **8**: 313-329

[3] Meltzer, Evelyne, 1994, Global Overview of Straddling and Highly Migratory Fish Stocks: The Non-sustainable Nature of High Seas Fisheries, *Ocean Development and International Law* **25**, 255-344.

[4] 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).

[5] McKelvey, Robert W., Leif K. Sandal and Stein I. Steinshamn, 2002, Fish wars on the high seas: A straddling stock competition model, *International Game Theory Review* **4**: 53 - 69.

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


a)
45 o
Rα
ΦR
Rα
S
S crit β
R
R crit
R0
R̃
K

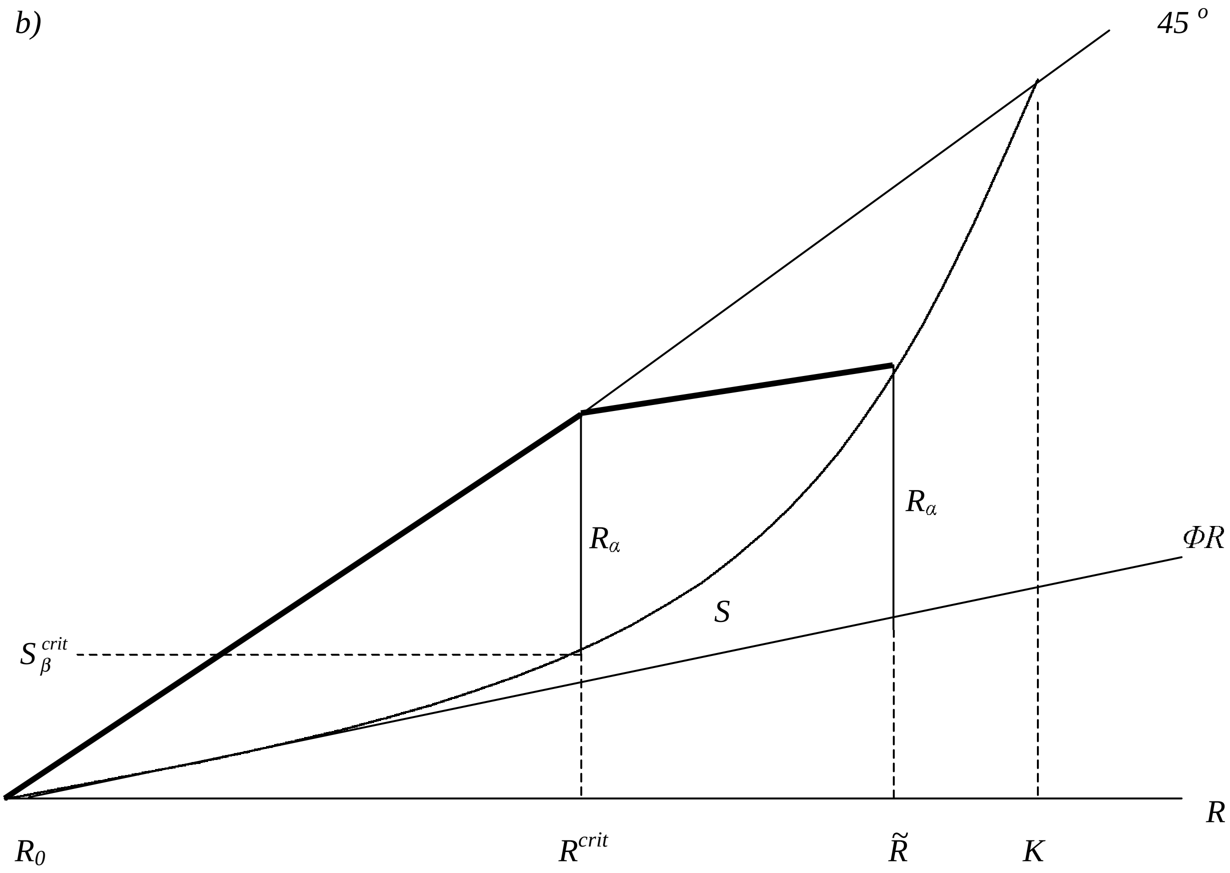

b)
45 o
Rα
Rα
ΦR
S
S crit β
R
R0
R crit
R̃
K

Figure 1.

Each recruitment level R on the interval $0 < R < \tilde{R}$ meets the steady-state feasibility requirement, with the high-seas harvest pinching out below $R = R^{crit}$. No steady-state recruitment level R on $\tilde{R} < R < K$ is feasible, since there $R^{\alpha} < F^{(-1)}(R) - \Phi R$. Panel *b* shows the case when $R_0 = 0$. The area above the thick line and the *S*-curve, but below the 45^{o}-line, is the high seas harvest. (In this figure we have skipped the hats on the steady-state values of R and S_{β}.)

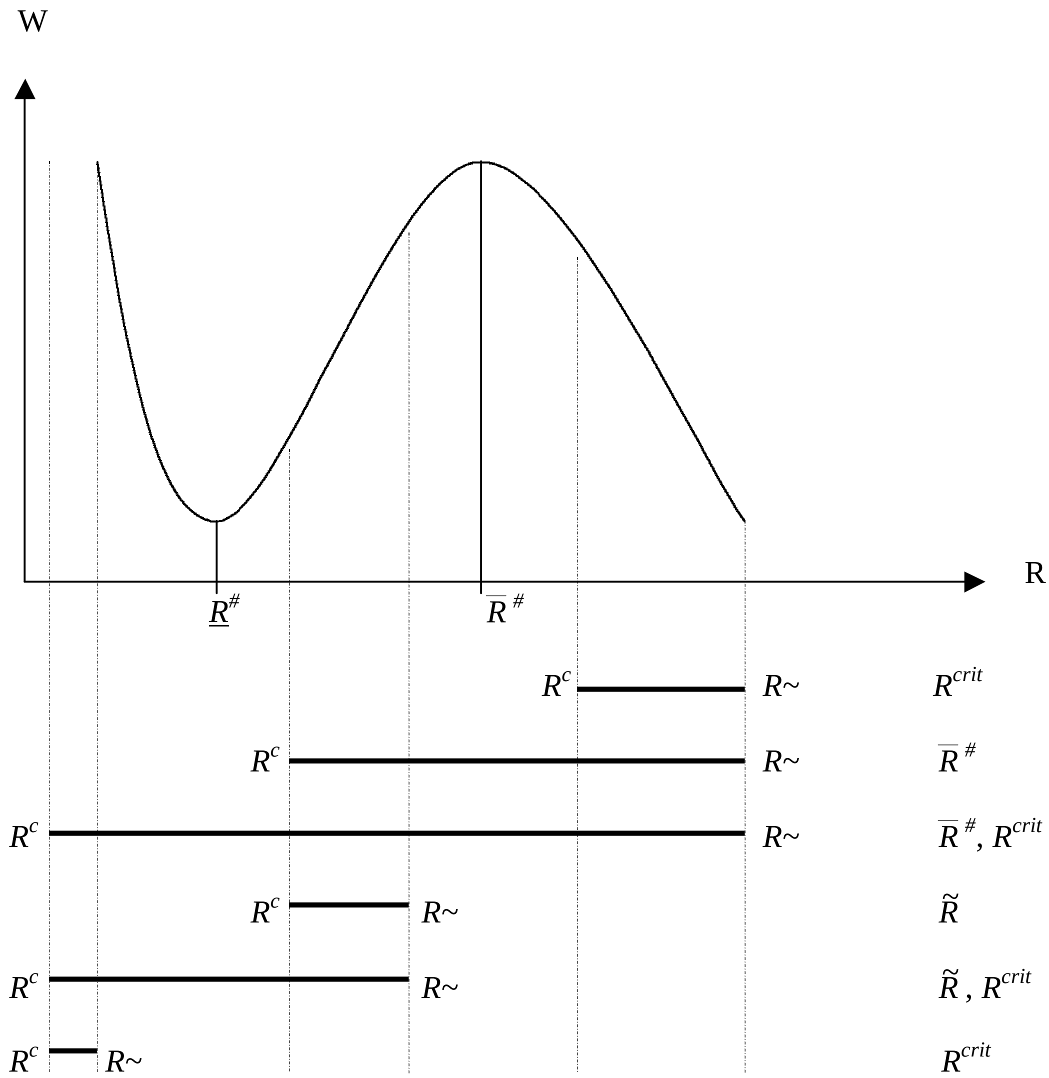


Figure 2.
This figure summarizes the possibilities under case B_2. The solid horisontal lines indicate the positions of R^{crit} and $\tilde{R}$ relative to $\underline{R}^{\#}$ and $\overline{R}^{\#}$. R^{crit} is indicated by R^c and $\tilde{R}$ is indicated by R~. The rightmost column under the graph indicates the optimal policies with respect to $\hat{R}$ in each of the six cases.

.

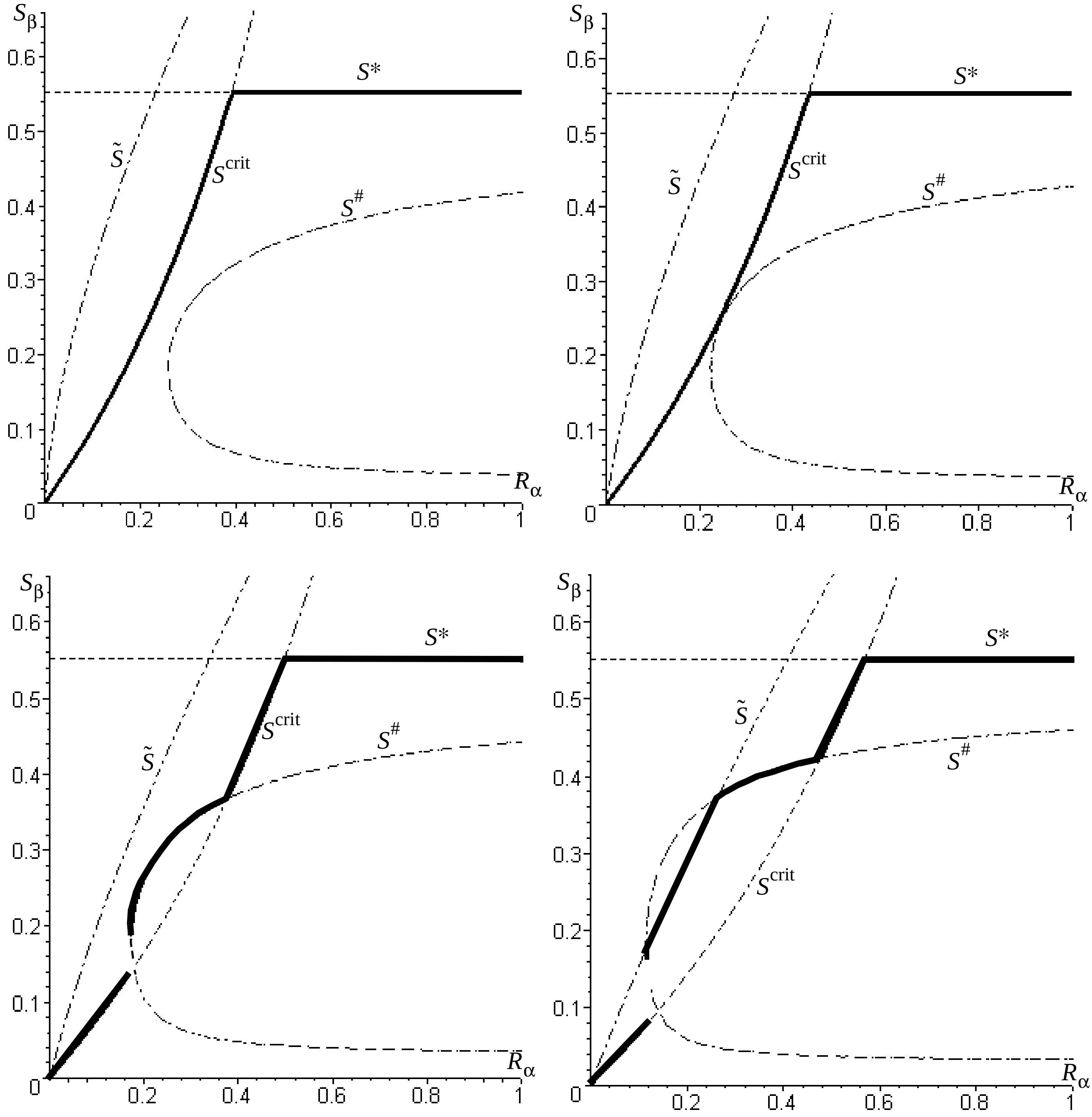


Figure 3

The horizontal line is S^*. Note that $S^\#$ is a multivalued function. Typically no value for small R_α and two for high R_α. The upper branch of $S^\#$ represents a local maximum and the lower a local minimum. Only the part of $S^\#$ between $\tilde{S}$ (exclusive high sea harvesting) and S^{crit} represents admissible solutions for the mixed harvesting. The optimal solutions are given by the thick curve. The panel is produced by the standard model given by $\pi_\theta(x) = 1 - 0.35/x$, $\pi_\beta(x) = 1 - 0.30/x$ and $F(x) = 2x/(1+x)$. The discounting factor $\gamma = 0.95$ and the panels are produced with $\theta = 0.55, 0.61, 0.70$ and 0.80 from upper left to lower right. Scale is relative to the Carrying Capasity (K).