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Analysis of a Highly Migratory Fish Stocks Fishery: A Game Theoretic Approach

TOYOKAZU NAITO
STEPHEN POLASKY
Oregon State University

Abstract *This paper develops a two period noncooperative game-theoretic model of a Highly Migratory Fish Stocks (HMFS) fishery. In each period, the fish stock migrates from the Exclusive Economic Zone (EEZ) of a coastal state into the high seas, where distant water fishing (DWF) harvesters may harvest. We show that having an EEZ improves total welfare by reducing total harvest and that the degree of the welfare improvement increases when the number of harvesters in an HMFS fishery increases. We also show that an increase in the number of DWF harvesters leads to a larger harvest and rent dissipation. With open-access in the second stage, resource rent is totally dissipated for DWF harvesters, but not for the coastal state harvesters, which still earn positive rent.*

Key words Common property resources, highly migratory fish stocks, noncooperative dynamic game, straddling fish stocks.

Introduction

There is great concern at present that fish stocks are being depleted by overfishing. In part, overfishing is caused by the common property nature of fishery resources. High seas fishery resources such as highly migratory fish stocks and straddling fish stocks may suffer from over-fishing because one country does not take into account the detrimental effect that its harvest has on other fishing countries.[1] This problem has brought conflicts between coastal states and distant water fishing (DWF) countries. Recently, the United Nations has identified the importance of resolving this conflict and has sponsored a series of conferences to discuss the conservation and management of these types of stocks.

Two of the most dramatic examples of the issue of straddling fish stocks are found in the Grand Bank and the Central Bering Sea. The groundfish stocks on the Grand Bank off Newfoundland are found both within and outside Canada's Exclusive Economic Zone (EEZ). Although an international organization, the Northwest Atlantic Fisheries Organization (NAFO), establishes and enforces a cooperative management regime among members, non-NAFO countries enter the Grand Bank, which has caused international conflict (*i.e.*, the Canada-Spain "turbot war").[2] In the Central Bering Sea, there is a pocket that is outside both the United States and the Russian EEZ (the Donut Hole). The groundfish in the Donut Hole are harvested by

Toyokazu Naito is a postdoctoral research associate in the Department of Forest Resources; Stephen Polasky is associate professor in the Department of Agricultural and Resource Economics; both are at Oregon State University, Corvallis, OR 97331-3601; e-mail: naitot@ucs.orst.edu and steve.polasky@orst.edu, respectively.

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[1] According to the 1982 United Nations Convention on the Law of the Sea, highly migratory and straddling fish stocks are defined as stocks that include species occurring either within the Exclusive Economic Zone (EEZ) of two or more coastal states, or both within the coastal state EEZ and the adjacent high seas.

[2] For details, see discussions by Kaitala and Munro (1993), Munro (1996), and Missios and Plourde (1996).

several DWF countries. In the middle of the 1980s and early 1990s, DWF harvesters rapidly increased harvest of pollock from the Donut Hole, which is thought to be largely responsible for the crash of the pollock stock in 1992.

Examples of the problem of highly migratory fish stocks are provided by the tuna and salmon fisheries. The southern bluefin tuna is a highly migratory species, spending periods of its life cycle both in and out of the Australian EEZ. Bluefin tuna are harvested as juveniles by Australia within its EEZ, and as adults by several DWF countries on the high seas. The yellowfin tuna migrates along the Pacific coast from the United States to Chile and out to the high seas. Yellowfin tuna are also harvested by coastal states and DWF countries. Another example of highly migratory fish stocks are Pacific salmon. Anadromous species, like salmon, hatch in rivers and then migrate into other countries' EEZ's and the high seas.

In this paper, we focus on the case of highly migratory fish stocks (HMFS). We analyze the consequences of noncooperative management of an HMFS fishery. Specifically, we analyze the following: (1) what effect does the existence of an EEZ have on noncooperative management of an HMFS fishery; (2) how much does a noncooperative equilibrium differ from the socially optimal outcome (*i.e.*, a cooperative management outcome); and (3) how does noncooperative equilibrium change with a change in the number of DWF harvesters?

To answer these questions, we construct a two-period noncooperative game-theoretic model. The model consists of two stages in each period. In the first stage, the fish stock is located in the EEZ of a coastal state and can be harvested only by the coastal state harvesters. We assume that the government of the coastal state regulates the fishing activity within the EEZ to maximize results for the coastal state (*i.e.*, they act as a single harvester).[3] In the second stage, the fish stock migrates to the high seas and DWF harvesters simultaneously harvest from the remaining fish stock. At the conclusion of period one, the remaining stock migrates back to the coastal state EEZ, the stock grows according to a biological growth function, and period two begins. Unit harvest costs are assumed to be an increasing function of the proportion of the stock harvested. We solve the model for a feedback (subgame perfect) equilibrium.[4]

With an HMFS that begins the period in the coastal state EEZ, the coastal state harvesters can harvest the stock prior to DWF harvesters. We refer to this model as a Stackelberg model with the coastal state harvesters in the role of the Stackelberg leader. In order to examine the effect of having an EEZ on an HMFS fishery, we compare the results of the Stackelberg model to a Cournot type model with no EEZ. In the Cournot model, the coastal state and DWF harvesters simultaneously choose harvest levels in stage one and two.[5] We show that having the EEZ in an HMFS fish-

[3] Clarke and Munro (1987 and 1991) use a model in which a coastal state allows a DWF harvester to harvest by charging a fee. They analyze the terms and conditions set by the coastal state for the DWF harvester to harvest within the EEZ.

[4] We distinguish a feedback equilibrium from a closed-loop equilibrium. A feedback strategy depends on both the state and time; on the other hand, a closed-loop strategy depends on the initial condition as well as the state and time (see Reinganum 1985; Kamien and Schwartz 1991).

[5] The Cournot model, a simultaneous move game, has been utilized to show the inefficiency of noncooperative fisheries (Levhari and Mirman 1980; Fischer and Mirman 1992, 1996), and shows the difference between a feedback (subgame perfect) equilibrium and an open-loop (Nash) equilibrium (Eswaran and Lewis 1984, 1985; Reinganum and Stokey 1985; Negri 1990). Previously, several papers have solved for open-loop equilibrium (Chiarella *et al*. 1984; Kaitala, Hämäläinen, and Ruusunen 1985; and Mohr 1988). However, open-loop equilibrium ignores the strategic effect present in a feedback equilibrium; hence, it is a valid equilibrium concept if all players can commit to a path of harvests over time at the initial instant. This concept is not appropriate when players have the ability to choose harvest at time t based on conditions (stock level) at time t. In this case, it is appropriate to use a feedback solution concept, which is equivalent to a subgame perfect equilibrium. In special cases, open-loop and feedback solutions coincide (Clark 1980; Plourde and Yeung 1989).

ery, of the type modeled in this paper, reduces total harvest level. This result occurs because the EEZ reduces the number of harvesters that may harvest in the first stage. Levhari and Mirman (1980) also compare a Stackelberg and Cournot model. In their duopoly model, each harvester harvests only once per period. They show that sequential harvest (Stackelberg) yields greater equilibrium harvests, given the stock size, and smaller equilibrium steady state stock than does simultaneous harvest (Cournot). As in the traditional Stackelberg model, there is a strategic effect for the leader to expand harvest in order to get the follower to contract harvest. This strategic effect is present in our model as well, but it is dominated by the effect of reducing the number of harvesters at the first stage.

We also examine the welfare consequences of instituting an EEZ in an HMFS fishery. Instituting an EEZ increases equilibrium rents obtained from the HMFS fishery. Having an EEZ allows the coastal state to act as a sole harvester in the first stage. Because harvest costs are an increasing function of the ratio of harvest to stock, the coastal state can obtain low harvest costs (large rents) in the first stage relative to the Cournot case. The Stackelberg equilibrium with an EEZ is not first best because there are multiple harvesters in the second stage. Previously, several papers have undertaken welfare analyses. Using a simulation model, Kennedy (1987) finds that rents are distributed asymmetrically among two harvesters in a Stackelberg game and that the equilibrium is inefficient. Also, using nonlinear programming, Kennedy and Pasternak (1991) demonstrate the potential gains from moving to a cooperative fishery. Karp (1992) and Mason and Polasky (1997) solve for a Markov perfect equilibrium and find the optimal number of harvesters in the common property resources.

In addition, we use the Stackelberg model to examine how changes in the number of DWF harvesters affects both the equilibrium harvest level and resource rents. An increase in the number of DWF harvesters reduces total rents and increases total equilibrium harvest level; harvest by the coastal state and the collective DWF harvesters increases, but the harvest level of the individual DWF harvesters is reduced.[6] We also analyze a bionomic equilibrium (Gordon 1954) of open-access in the second stage. With a bionomic equilibrium, resource rent is totally dissipated for DWF harvesters, but the coastal state still earns a positive resource rent. This result contrasts with Cournot models in which all resource rents are dissipated (Negri 1990). Moreover, the degree of the total welfare improvement by having an EEZ increases as the number of fishing harvesters increases.

In the Stackelberg model, we assume that the government of the coastal state is able to enforce a cooperative solution for harvest within the EEZ, which maximizes the rents from the fishery to the coastal state. In principle, the government of the coastal state has the authority to regulate the fishery so that the cooperative solution may be achieved [*e.g.*, setting the total allowable catch (TAC) at the cooperative solution amount]. In practice, because of political pressure from various competing groups within the coastal state or poor enforcement, the government may not be able to achieve this outcome. For example, it is argued that the collapse of the ground fish stocks on the Grand Banks and the cod stocks within Iceland's EEZ were caused by overfishing by the coastal state (Hannesson 1995). We consider the case where harvesters within the EEZ act noncooperatively and show that harvest within the coastal state increases and rents fall.

On the other hand, we assume there is not a cooperative agreement between countries that may harvest from an HMFS fishery. Enforcement power is much

[6] Mason and Polasky (1994) analyze conditions in which there is a fixed cost of entry and show conditions under which the incumbent would deter or allow entry. They show that potential entry increases the equilibrium harvest of incumbent firm.

higher within a country than it is across international boundaries. It may be impossible to impose decisions that run counter to the best interests of a particular country. Examples of international management of the groundfish, tuna, and salmon stocks mentioned above are examples where international management of an HMFS fishery has not been efficient. Some examples of international cooperation on harvesting, at least for a time, do exist (*e.g.*, the International Whaling Commission). Some of the previous game-theoretic literature on fisheries has utilized cooperative game models to analyze transboundary (or shared) stocks fisheries (Munro 1979, 1987; Vislie 1987; Kaitala and Pohjola 1988; Ehtamo and Hämäläinen 1993). Missios and Plourde (1997) and Ferrara and Missios (1996) use cooperative game models to analyze the case of transboundary fish stocks for two countries. In our model, we also solve for the socially optimal (cooperative) solution and show the relative inefficiency of our noncooperative solutions.

This paper is organized as follows. The following section constructs a model of an HMFS fishery and solves for a subgame perfect equilibrium. The third section analyzes the effect of entrants on the equilibrium harvest and resource rent. The fourth section derives a subgame perfect equilibrium in a Cournot model. In the fifth section, the Stackelberg and Cournot models are compared. Outcomes in both of these models are compared with the socially optimal solution. Concluding remarks are presented in the last section.

Stackelberg Model

Suppose there are $n + 1$ harvesters including one coastal state and n symmetric DWF harvesters denoted as $i = 1$ and $i = 2, 3, \ldots, n + 1$, respectively. Each harvester i chooses the harvest level h_t^i in period t, $t = 1, 2$. Within the coastal state, we assume the government can regulate the fishery so that the cooperative solution is achieved (*e.g.* setting the total allowable catch at the cooperative solution amount).[7] Let S_t be the fish stock available for harvest at the beginning of period t.

In each period, there are two stages. In the first stage, the fish stock, S_t, is

[7] Suppose the coastal government cannot regulate the coastal state fishing fleet, which consists m fishing harvesters (*i.e.*, m decision-makers). In this case, there are $m + n$ harvesters in the model. Hence, the total fish harvest in period t, H_t, is the sum of the harvest by all $m + n$ harvesters: $H_t = \sum_{k=1}^{m} h_t^k + \sum_{i=1}^{n} h_t^i = H_t^1 + H_t^{\sim 1}$; $t = 1, 2$.

In this case, the subgame perfect outcomes for the m harvesters in the coastal state change to:

$$h_1^k = \tilde{\Psi} \frac{P}{(m+1)\alpha} S_1; \quad k = 1, 2, \ldots, m$$

where

$$\tilde{\Psi} = 1 - \left(1 - \tilde{\Phi} \frac{nP}{(n+1)\alpha}\right) \frac{\beta P}{(m+1)^2 \alpha} \text{ and } \frac{55}{64} < \tilde{\Psi} \leq 1$$

and for the n DWF harvesters change to:

$$h_1^i = \tilde{\Phi}\left(1 - \tilde{\Psi} \frac{P}{2\alpha}\right) \frac{P}{(n+1)\alpha} S_1; \quad i = 1, 2, \ldots, n$$

where

$$\tilde{\Phi} = 1 - \left[1 - \frac{mP}{(m+1)\alpha}\right] \frac{\beta P}{(n+1)^2 \alpha} \text{ and } \frac{7}{8} < \tilde{\Phi} \leq 1.$$

These outcomes show that if $m \geq 2$, the harvest levels for all harvesters become smaller than when $m = 1$. However, they do not change the qualitative results of the analysis.

within the coastal state EEZ and the coastal state chooses harvest level h_t^1. In the second stage, the remaining stock, $S_t - h_t^1$, migrates out of the coastal state's EEZ and into the adjacent high sea. The n symmetric DWF harvesters then simultaneously choose level h_t^i (for $i = 2, 3, \ldots, n + 1$). Since all $n + 1$ harvesters harvest fish from the same fish stock, the total fish harvest in period t, H_t, is the sum of the harvest by all $n + 1$ harvesters:

$$H_t = h_t^1 + \sum_{i=2}^{n+1} h_t^i = h_t^1 + H_t^{\sim 1}; \quad t = 1, 2, \tag{1}$$

where $H_t^{\sim 1}$ denotes the aggregate harvest by the n DWF vests. Total harvest is non-negative and cannot exceed the stock, $0 \le H_t \le S_t$.

At the conclusion of period t, the remaining stock migrates back to the coastal state EEZ, and period $t + 1$ begins with the coastal state facing a stock of size S_{t+1}. This new stock size includes both the stock remaining after harvesting in period t, plus growth which occurs between period t and period $t + 1$. For simplicity, we assume that stock growth is governed by a linear function. One way to think about the linear growth function is that it is an approximation of a logistic or other growth function in the range of low stock size, which occurs in a fishery with high fishery effort, before density dependent effects have much influence. Hence, the fish stock dynamics between period 1 and period 2 is

$$S_{t+1} = (1 + r)S_t - H_t; \quad t = 1, 2 \tag{2}$$

where r is the biological growth rate parameter ($r > 0$).

We assume that the unit cost of harvesting fish increases with the ratio of harvest to stock. Typically as stock level falls, it becomes more difficult to harvest fish and unit harvest costs should increase. The cost of harvesting fish, C_t^i, can be written for the coastal state and for n DWF harvesters, respectively as

$$C_t^1 = \alpha \frac{h_t^1}{S_t} h_t^1 \text{ and } C_t^i = \alpha \frac{H_t^{\sim 1}}{S_t - h_t^1} h_t^i; \quad i = 2, 3, \ldots, n + 1; \ t = 1, 2, \tag{3}$$

where α is a cost parameter ($\alpha > 0$).

The profit earned by harvester i from the fishery in period t, π_t^i, is the difference between the revenue and the cost in each period. The unit price of the harvested fish is assumed to be constant at P (*i.e.*, perfectly elastic demand because there are many substitutes in the world market) with $0 < P < \alpha$.[8] Alternatively, we could assume that price is a linear function of the total harvest within a stage: $P(x_t) = a - x_t$, where x_t

[8] To get an interior solution for the subgame perfect equilibrium in the Stackelberg model, we need: $0 < P < 2\alpha$. If P is greater than or equal to 2α, which implies price level is high relative to cost, a coastal state will fish out all stock in the first stage (*i.e.*, the game is over after the first stage). For the case of the Cournot model in section 4, we need: $0 < P < 3\alpha$; because, if P is greater than or equal to 3α, all harvesters will harvest all stock in the first stage. On the other hand, for an open-access bionomic equilibrium in section 3, we need a stronger assumption: $0 < P < \alpha$, because to get an interior solution, the harvest level by the collective DWF harvesters cannot be greater than or equal to the remaining stock in the first stage:

$$\lim_{n\to\infty} H_1^{\sim 1} = \frac{P}{\alpha}(S_1 - h_1^1) < S_1 - h_1^1.$$

Therefore, we take the strongest assumption, $0 < P < \alpha$, for the price level in this paper.

equals h_t^1 in stage one and x_t equals $H_t^{\sim 1}$ in stage two. This assumes a downward sloping demand curve does not affect the positive analysis any differently than would making costs increasingly convex in current stage harvest.[9] On the other hand, the welfare analysis becomes quite complex because there are both common property and market power distortions to consider. For further analysis of the welfare issues in this case see Mason and Polasky (1997). The profits earned in period t by the coastal state and the n DWF harvesters are, respectively

$$\pi_t^1 = h_t^1\left(P - \alpha\frac{h_t^1}{S_t}\right) \text{ and } \pi_t^i = h_t^i\left(P - \alpha\frac{H_t^{\sim 1}}{S_t - h_t^1}\right); \quad i = 2, 3, \ldots, n+1; \quad t = 1, 2. \qquad (4)$$

All harvesters are assumed to have complete information, that is, the payoff functions (profits) are common knowledge.

To solve our two-period Stackelberg model for a subgame perfect equilibrium, we use backward induction and begin at the second stage in period 2 (*i.e.*, the last stage of the game). When the second stage in period 2 is reached, the n DWF harvesters face the following profit maximization problem:

$$\max_{h_2^i} \pi_2^i(h_2^1, h_2^2, \ldots, h_2^{n+1}) = \max_{h_2^i} \pi_2^i = h_2^i\left(P - \alpha\frac{H_2^{\sim 1}}{S_2 - h_2^1}\right); \quad i = 2, 3, \ldots, n+1. \qquad (5)$$

We take the first order condition of equation (5) and set it equal to zero to find a typical harvester's best response function.[10] We sum over the n identical first-order conditions and solve for the profit maximizing harvest level for each DWF harvester i:

$$h_2^{i*} = \frac{P}{(n+1)\alpha}(S_2 - h_2^1); \quad i = 2, 3, \ldots, n+1 \qquad (6)$$

where h_2^{i*} is the equilibrium harvest choice of DWF harvester in period 2, which is a function of the remaining stock after the coastal state harvest.

At the first stage in period 2, the coastal state's problem is

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[9] As noted by a referee, when harvest from the two stages are perfect substitutes so that demand is a function of total harvest in a period, *i.e.*, $P(H_t) = a - H_t$, there will be an additional strategic effect in the model. In this case, the coastal state (Stackelberg leader) will increase harvest in order to decrease harvest in the second stage by the DWF harvesters. We do not analyze this effect in our model.

[10] The second-order conditions are satisfied for a maximum in all two stages and two periods. In the first stage in both periods, the second-order conditions are negative:

$$\frac{\partial^2 \pi_t^1}{\partial (h_t^1)^2} = -\frac{2\alpha}{S_t} < 0; \quad t = 1, 2.$$

Also, in the second stage in both periods, the second-order conditions are also negative:

$$\frac{\partial^2 \pi_t^i}{\partial (h_t^i)^2} = -\frac{2\alpha}{S_t - h_t^1} < 0; \quad t = 1, 2.$$

In the Cournot model in section 4, the second-order conditions are also satisfied for a maximum in the same way. We also note that we have a unique (stable) equilibrium in the second stage, as in the standard Cournot model with linear demand and constant returns to scale, because the absolute value of the second derivative of a firm's profit function with respect to own harvest is greater than the absolute value of the second derivative of the firm's profit function with respect to the rivals' harvests (Tirole, p. 226).

$$\max_{h_2^1} \pi_2^1(h_2^1) = \max_{h_2^1} h_2^1\left(P - \alpha\,\frac{h_2^1}{S_2}\right). \tag{7}$$

Solving the first-order condition of the maximization problem in equation (7), the optimal harvest level for the coastal state in period 2 is

$$h_2^{1*} = \frac{P}{2\alpha}\,S_2. \tag{8}$$

Substituting this optimal harvest level for the coastal state into equation (6), the subgame perfect outcome in period 2 is

$$\begin{aligned} &\left[h_2^{1*}, h_2^{2*}(h_2^{1*}), \ldots, h_2^{n+1*}(h_2^{1*})\right] \qquad (9)\\ &= \left[\frac{P}{2\alpha}\,S_2, \left(1 - \frac{P}{2\alpha}\right)\frac{P}{(n+1)\alpha}\,S_2, \ldots, \left(1 - \frac{P}{2\alpha}\right)\frac{P}{(n+1)\alpha}\,S_2\right]. \end{aligned}$$

The harvest for the coastal state is equal to the optimal solution for a sole harvester (harvesting once) while the harvest at the second stage for each DWF harvester is the Cournot equilibrium harvest given the stock that remains. Note that there is no strategic effect for the coastal state in the second period as the payoffs for the coastal state are not affected by the DWF harvest in the second period.

Substituting the subgame perfect outcome in equation (9) into both the objective function of the coastal state in equation (7) and that of the n DWF harvesters in equation (5), the one-period optimal value function for the coastal state is

$$V_2^{1*}(S_2) = \frac{P^2}{4\alpha}\,S_2 \tag{10}$$

and for the n DWF harvesters is

$$V_2^{i*}(S_2) = \left(1 - \frac{P}{2\alpha}\right)\frac{P^2}{(n+1)^2\alpha}\,S_2; \quad i = 2, 3, \ldots, n+1. \tag{11}$$

The optimal value function $V_t^i(S_t)$ is defined as the maximum value that can be obtained starting at time t with fish stock S_t.

Next, we consider harvest choice in the first period. Applying the method of backward induction, the problem for the n DWF harvesters at the second stage in period 1 can be written as

$$\begin{aligned} &\max_{h_1^i} \pi_1^i(h_1^1, h_1^2, \ldots, h_1^{n+1}) \qquad (12)\\ &= \max_{h_1^i} h_1^i\left(P - \alpha\,\frac{H_1^{\sim 1}}{S_1 - h_1^1}\right) + \beta\left[V_2^{i*}(S_2)\right]; \quad i = 2, 3, \ldots, n+1 \end{aligned}$$

where β is the discount factor ($0 < \beta < 1$). The first term on the right-hand-side of the equation is the current payoff and the second term is the discounted one-period optimal value function in period 2. By including the latter term, the optimal decision by each DWF harvester takes into consideration the effect of harvest not only on current period (period 1) profit but also for the future period (period 2) profit.

We substitute the one-period optimal value function in equation (11) into the profit equations in equation (12), and further substitute the stock growth equation in (2). The optimization problem for the DWF harvesters can be rewritten as

$$\max_{h_1^i} h_1^i\left(P - \alpha \frac{H_1^{\sim 1}}{S_1 - h_1^1}\right) + \left(1 - \frac{P}{2\alpha}\right)\frac{\beta P^2}{(n+1)^2\alpha}\left[(1+r)S_1 - H_1\right]; \quad i = 2, 3, \ldots, n+1 \tag{13}$$

where the size of HMFS in period 1, S_1, is given exogenously. We find the best response function for each of the n DWF harvesters and sum over these n first-order conditions to find the profit maximizing harvest level for the DWF harvesters in period 1. The equilibrium harvest of a typical DWF harvester in period 1 as a function of remaining stock, $S_1 - h_1^1$, is:

$$h_1^{i*} = \Phi \frac{P}{(n+1)\alpha}(S_1 - h_1^1); \quad i = 2, 3, \ldots, n+1 \tag{14}$$

where

$$\Phi = 1 - \left(1 - \frac{P}{2\alpha}\right)\frac{\beta P}{(n+1)^2\alpha} \text{ and } \frac{7}{8} < \Phi \le 1.$$

At the first stage in period 1, the coastal state's problem is

$$\max_{h_1^1} \pi_1^1\left[h_1^1, h_1^2(h_1^1), \ldots, h_1^{n+1}(h_1^1)\right] = \max_{h_1^1} h_1^1\left(P - \alpha\frac{h_1^1}{S_1}\right) + \beta\left[V_2^{1*}(S_2)\right]. \tag{15}$$

Using the optimal value function of the coastal state in equation (10), fish dynamics in equation (2), harvest expressions of the n DWF harvesters in equation (14) into (15), the optimization problem for the coastal state becomes

$$\max_{h_1^1} h_1^1\left(P - \alpha\frac{h_1^1}{S_1}\right) + \frac{\beta P^2}{4\alpha}\left[(1+r)S_1 - h_1^1 - \Phi\frac{nP}{(n+1)\alpha}(S_1 - h_1^1)\right]. \tag{16}$$

Solving the first-order condition gives the optimal harvest level for the coastal state in period 1:

$$h_1^{1*} = \Psi \frac{P}{2\alpha} S_1 \tag{17}$$

where

$$\Psi = 1 - \left(1 - \Phi \frac{nP}{(n+1)\alpha}\right)\frac{\beta P}{4\alpha} \text{ and } \frac{55}{64} < \Psi < 1.$$

Substituting this solution into the best response function of n DWF harvesters in equation (14), the subgame perfect outcome in period 1 is

$$\left[h_1^{1*}, h_1^{2*}(h_1^{1*}), \ldots, h_1^{n+1*}(h_1^{1*})\right] \tag{18}$$

$$= \left[\Psi \frac{P}{2\alpha} S_1, \Phi\left(1 - \Psi \frac{P}{2\alpha}\right)\frac{P}{(n+1)\alpha} S_1, \ldots, \Phi\left(1 - \Psi \frac{P}{2\alpha}\right)\frac{P}{(n+1)\alpha} S_1\right].$$

Note that the coastal state chooses to harvest a smaller proportion of stock in the first period than in the second [equation (9) times Ψ]. Similarly, each DWF harvester chooses to harvest a smaller proportion of stock in the first period than in the second [$\Phi P/(n + 1)\alpha < P/(n + 1)\alpha$]. These results occur because there is an additional user cost of harvest in the first period (*i.e.*, harvesting less, yields more stock for the second period). However, there is a countervailing strategic effect. By increasing harvest in the first stage of the first period, the coastal state can get DWF harvesters to reduce harvest in the second stage of period one. This reduction is advantageous for the coastal state in period 2. Similarly, an increase in DWF harvest at the second stage of period one will cause the coastal state to reduce harvest in the first stage of period 2. Both of these strategic effects tend to increase period one harvest above what it would otherwise have been.

To obtain the two-period optimal value functions, we substitute the subgame perfect outcome in equation (18) into both the objective function for the coastal state in equation (16) and the objective function for the n DWF harvesters in equation (13). The following value functions are obtained for the coastal state

$$V_1^{1*} = \left[2\Psi - \Psi^2 + r\beta + \beta\left(1 - \Psi \frac{P}{2\alpha}\right)\left(1 - \Phi \frac{nP}{(n+1)\alpha}\right)\right]\frac{P^2}{4\alpha} S_1 \tag{19}$$

and the DWF harvesters,

$$V_1^{i*} = \left[\left\{(n+1)\Phi - n\Phi^2\right\}\left(1 - \Psi \frac{P}{2\alpha}\right) + r\beta\left(1 - \frac{P}{2\alpha}\right)\right. \tag{20}$$

$$\left. + \beta\left(1 - \frac{P}{2\alpha}\right)\left(1 - \Psi \frac{P}{2\alpha}\right)\left(1 - \Phi \frac{nP}{(n+1)\alpha}\right)\right]\frac{P^2}{(n+1)^2\alpha} S_1; \quad i = 2, 3, \ldots, n+1.$$

In the brackets in both solutions, the first and second term show the parts of resource rents from period 1, and the third and last term present the parts of resource rents from period 2, which is discounted by β.

The Effect of a Change in the Number of DWF Harvesters

A change in the number of DWF harvesters affects equilibrium harvest levels and resource rents of both the coastal state and DWF harvesters. We analyze both a marginal increase in the number of DWF harvester and open access (bionomic) equilibrium.

A Marginal Increase in the Number of DWF Harvesters

Using the solution to the two-period model developed in the previous section, the partial derivatives of the equilibrium harvest levels for the coastal state, each DWF harvester, and the collective DWF harvesters ($H_1^{\sim 1*} = nh_1^{i*}$) with respect to the parameter n are:

$$\frac{\partial h_1^{1*}}{\partial n} > 0, \quad \frac{\partial h_1^{i*}}{\partial n} < 0, \quad \frac{\partial H_1^{\sim 1*}}{\partial n} > 0.$$

These results lead to the following proposition (see the appendix for proofs of all propositions).

PROPOSITION 1: *An increase in the number of DWF harvesters in an HMFS fishery increases the equilibrium harvest level in the first period for the coastal state and the collective DWF harvesters, but reduces the equilibrium harvest level for the individual DWF harvesters.*

This result is explained by dynamic stock and static externalities. An increase in the number of DWF harvesters increases the proportion of stock harvested by the collective DWF harvesters, which raises cost and lowers profit for each DWF harvester. The coastal state can anticipate the larger harvest by the DWF harvesters and realize that there is less value for the coastal state to conserve the stock for the second period. Consequently, the coastal state increases its harvest level in the first period. As a result, stock levels are lower in stage 2 of periods 1 and 2 than they are without the increase in the number of DWF harvesters.

We next examine the effect of an increase in the number of DWF harvesters on the two-period optimal value functions for the coastal state and DWF harvesters. Recall that these functions consist of the first period pay-off and the discounted second period optimal value function. Partial derivatives of these two-period optimal value functions with respect to the parameter n are:

$$\frac{\partial V_1^{1*}}{\partial n} < 0, \quad \frac{\partial V_1^{i*}}{\partial n} < 0$$

which we summarize in the following proposition.

PROPOSITION 2: *An increase in the number of DWF harvesters in an HMFS fishery decreases the resource rent for all harvesters (coastal and DWF harvesters).*

In the second period, the discounted optimal value function is positively related to the stock size [equations (10) and (11)]. Using proposition 1, an increase in the number of DWF harvesters in the first period lowers the resource rent for the coastal state (as the stock size in period two is reduced). For the individual DWF harvesters, an increase in the number of DWF harvesters also increases the harvesting cost for each DWF harvester. The DWF harvesters encounter both static and dynamic externalities and, therefore, their individual resource rents decline. The coastal state is also made worse by an increase in the number of DWF harvesters because more of the remaining stock in the second stage of period 1 will be harvested, leaving less for the coastal state to harvest in period 2.

Open Access Equilibrium

Next we analyze open-access (bionomic) equilibrium (Gordon 1954). If DWF harvesters earn positive profit (*i.e.*, have positive optimal value functions), then additional DWF harvesters are attracted to the fishery. Entry will continue until the fishery reaches a bionomic equilibrium in which all operating DWF harvesters have zero profit (*i.e.*, their optimal value functions are zero) and resource rent is totally dissipated. In our model, this occurs when the number of DWF harvesters goes to infinity. Taking the limit of the harvest level by the collective DWF harvesters, found by summing equation (14) over all DWF harvesters, as n goes to infinity yields

$$\lim_{n\to\infty} H_1^{\sim 1} = \frac{P}{\alpha}(S_1 - h_1^1)$$

which is exactly the zero profit condition [using profit equation (4) with $t = 1$]:

$$\pi_1^i = 0 \Rightarrow P = \alpha \frac{H_1^{\sim 1}}{S_1 - h_1^1} \quad \text{or} \quad H_1^{\sim 1} = \frac{P}{\alpha}(S_1 - h_1^1).$$

Note that if price is greater than or equal to the cost parameter ($P \geq \alpha$), then in bionomic equilibrium the DWF harvesters will harvest all the remaining stock at the second stage in period 1 (the game is over after period 1).

By taking the limit as n goes to infinity, the two-period optimal value in the bionomic equilibrium for the coastal state is

$$\lim_{n\to\infty} V_1^{1*} = \left[2\Sigma - \Sigma^2 + r\beta + \beta\left(1 - \frac{P}{\alpha}\right)\left(1 - \Sigma\frac{P}{2\alpha}\right)\right]\frac{P^2}{4\alpha} S_1 > 0$$

where

$$\Sigma = \lim_{n\to\infty} \Psi = 1 - \frac{\beta P}{4\alpha}\left(1 - \frac{P}{\alpha}\right) \quad \text{and} \quad \frac{15}{16} < \Sigma < 1.$$

The two-period optimal value in the bionomic equilibrium for each DWF harvester is

$$\lim_{n\to\infty} V_1^{i*} = 0; \quad i = 2, 3, \ldots, \infty.$$

We summarize these results in the following proposition.

PROPOSITION 3: *Under a bionomic open-access equilibrium in an HMFS fishery, the coastal state harvesters earn positive resource rent but the resource rent for the DWF harvesters is totally dissipated.*

The rent earned by the coastal state is not totally dissipated even as the number of DWF harvesters goes to infinity because the coastal state has exclusive right to harvest the fish stock prior to DWF harvesters. The coastal state always earns a positive resource rent in the first period. The coastal state will earn additional rent in the second period if price is less than the cost parameter ($P < \alpha$).

The Cournot Model

We use a Cournot model to represent an HMFS fishery without an EEZ. To be comparable to the Stackelberg model, we use a two-period model which includes two stages in each period. In the Cournot model, however, each of the $n + 1$ harvesters may fish in each stage. Let h_{tk}^{j} represent the harvest level of harvester j in period t and stage k, $j = 1, 2, \ldots, n + 1$; $t, k = 1, 2$.

The total fish harvest in period t, H_t, is the sum of the harvest by all $n + 1$ harvesters in stage 1 and stage 2:

$$H_t = \sum_{j=1}^{n+1} h_{t1}^{j} + \sum_{j=1}^{n+1} h_{t2}^{j} = H_{t1} + H_{t2}; \quad t = 1, 2. \tag{21}$$

where H_{t1} and H_{t2} denote the total harvest by $n + 1$ harvesters in stages 1 and 2, respectively.

As in the Stackelberg model, harvest cost depends on total harvest and stock level in the stage. The costs of harvesting fish, C_{tK}^{j}, for each symmetric harvester in stage 1 and stage 2 are

$$C_{t1}^{j} = \alpha \frac{H_{t1}}{S_t} h_{t1}^{j} \quad \text{and} \quad C_{t2}^{j} = \alpha \frac{H_{t2}}{S_t - H_{t1}} h_{t2}^{j}; \quad j = 1, 2, \ldots, n + 1; \; t = 1, 2. \tag{22}$$

Profits earned by each harvester j from the fishery in stage 1 and stage 2 in period t, π_{tk}^{j}, are respectively (we keep assumption of a constant price P with $0 < P < \alpha$)

$$\pi_{t1}^{j} = h_{t1}^{j}\left(P - \alpha \frac{H_{t1}}{S_t}\right) \quad \text{and} \tag{23}$$

$$\pi_{t2}^{j} = h_{t2}^{j}\left(P - \alpha \frac{H_{t2}}{S_t - H_{t1}}\right); \quad j = 1, 2, \ldots, n + 1; \; t = 1, 2.$$

At the end of stage 2, the remaining stock migrates back to inshore and period $t + 1$ begins with a stock size S_{t+1}, which includes both the stock remaining after harvesting in period t plus growth which occurs between period t and period $t + 1$.

We use backward induction to solve our two-period (with two stages) Cournot model for a subgame perfect equilibrium. The $n + 1$ harvesters face the following profit maximization problem at the second stage in period 2:

$$\max_{h_{22}^{j}} \pi_{22}^{j}(h_{22}^{1}, h_{22}^{2}, \ldots, h_{22}^{n+1}) = \max_{h_{22}^{j}} h_{22}^{j}\left(P - \alpha \frac{H_{22}}{S_2 - H_{21}}\right); \quad j = 1, 2, \ldots, n + 1. \tag{24}$$

We take the first order condition of equation (24) and set it equal to zero to find a typical harvester's best response function for each of the $n + 1$ harvesters. We sum over the $n + 1$ identical first-order conditions and solve for the optimal harvest level for each harvester j:

$$h_{22}^{j*} = \frac{P}{(n + 2)\alpha}(S_2 - H_{21}); \quad j = 1, 2, \ldots, n + 1. \tag{25}$$

This equation shows the optimal harvest level for harvester j given the total harvest which is chosen by all harvesters at the first stage in period 2 (H_{21}).

Using the objective function in equation (24), the second stage value function for each harvester is found by substituting in the optimal harvest levels of the individual in equation (25) and its collective harvest level, $H^*_{22} (= \sum h^{j*}_{22})$

$$V^{j*}_{22} = \frac{P^2}{(n+2)^2 \alpha}(S_2 - H_{21}); \quad j = 1, 2, \ldots, n+1. \tag{26}$$

At the first stage in period 2, the harvester j's problem is

$$\max_{h^j_{21}} \pi^j_{21}(h^1_{21}, h^2_{21}, \ldots, h^{n+1}_{21}) \tag{27}$$

$$= \max_{h^j_{21}} h^j_{21}\left(P - \alpha \frac{H_{21}}{S_1}\right) + \left[V^{j*}_{22}\right]; \quad j = 1, 2, \ldots, n+1.$$

Substituting the half-period optimal value function in equation (26) and summing over the $n + 1$ identical first-order conditions, the optimal harvest level for each harvester at the first stage in period 2 is

$$h^{j*}_{21} = \Lambda \frac{P}{(n+2)\alpha} S_1; \quad j = 1, 2, \ldots, n+1 \tag{28}$$

where

$$\Lambda = 1 - \frac{P}{(n+2)^2 \alpha} \quad \text{and} \quad \frac{8}{9} < \Lambda \leq 1$$

Substituting the subgame perfect equilibrium in equation (28) and its collective harvest by all harvesters, $H^*_{21} (= \sum h^{j*}_{21})$, into the objective function in equation (27), the second period optimal value function for each harvester is

$$V^{j*}_{21}(S_2) = X \frac{P^2}{(n+2)^2 \alpha} S_2; \quad j = 1, 2, \ldots, n+1 \tag{29}$$

where

$$X = (n+2)\Lambda - (n+1)\Lambda^2 + 1 - \Lambda \frac{n+1}{n+2} \frac{P}{\alpha}.$$

Next, we turn to the first period. By the backward induction, the problem for the $n + 1$ harvesters at the second stage in period 1 can be written as

$$\max_{h^j_{12}} \pi^j_{12}(h^1_{12}, h^2_{12}, \ldots, h^{n+1}_{12}) \tag{30}$$

$$= \max_{h^j_{12}} h^j_{12}\left(P - \alpha \frac{H_{12}}{S_1 - H_{11}}\right) + \beta\left[V^{j*}_{22}(S_2)\right]; \quad j = 1, 2, \ldots, n+1.$$

Substituting the one-period optimal value function in equation (29) and the stock growth equation in equation (2) into equation (30), the optimization problem for each harvester can be rewritten as

$$\max_{h_{12}^j} h_{12}^j\left(P - \alpha \frac{H_{12}}{S_1 - H_{11}}\right) \tag{31}$$

$$+ X \frac{\beta P^2}{(n+2)^2\alpha}\left[(1+r)S_1 - H_{11} - H_{12}\right]; \quad j = 1, 2, \ldots, n+1.$$

We find the $n + 1$ first-order conditions (best response function) for each of the $n + 1$ harvesters and sum over those to find the profit maximizing harvest level for each harvester at the second stage in period 1.

$$h_{12}^{j*} = \Gamma \frac{P}{(n+2)\alpha}(S_1 - H_{11}); \quad j = 1, 2, \ldots, n+1 \tag{32}$$

where

$$\Gamma = 1 - X \frac{\beta P}{(n+2)^2\alpha} \quad \text{and} \quad \frac{608}{729} \ (\approx 0.834) < \Gamma \leq 1.$$

Substituting this solution and the total harvest level, $H_{12}^*(=\sum h_{12}^{j*})$, into the objective function for each harvester in equation (31), the one- and half-period optimal value function for each harvester is derived as

$$V_{12}^{j*} = Z \frac{P^2}{(n+2)^2\alpha}(S_1 - H_{11}) + X \frac{r\beta P^2}{(n+2)^2\alpha} S_1; \quad j = 1, 2, \ldots, n+1 \tag{33}$$

where

$$Z = (n+2)\Gamma - (n+1)\Gamma^2 + \beta X\left(1 - \Gamma \frac{n+1}{n+2}\frac{P}{\alpha}\right).$$

Given the second stage solution, we can derive the problem for each harvester at the first stage in period 1:

$$\max_{h_{11}^j} \pi_{11}^j(h_{11}^1, h_{11}^2, \ldots, h_{11}^{n+1}) \tag{34}$$

$$= \max_{h_{11}^j} h_{11}^j\left(P - \alpha \frac{H_{11}}{S_1}\right) + [V_{12}^{j*}]; \quad j = 1, 2, \ldots, n+1.$$

Substituting the one- and half-period optimal value function in equation (33), we find the best response function for each of the $n + 1$ harvesters and sum over these $n + 1$ first-order conditions to find the profit maximizing harvest level for each harvesters at the first stage in period 1:

$$h_{11}^{j*} = \Omega \frac{P}{(n+2)\alpha} S_1; \quad j = 1, 2, \ldots, n+1 \tag{35}$$

where

$$\Omega = 1 - Z \frac{P}{(n+2)^2 \alpha} \quad \text{and} \quad \frac{3840128}{4782969} \; (\approx 0.802) < \Omega \leq 1.$$

This is the subgame perfect equilibrium for the $n + 1$ harvesters at the first stage in period 1.

We now calculate the optimal harvest level for each harvester in period 1, which is denoted as $h_1^{j*} (= h_{11}^{j*} + h_{12}^{j*})$. By adding equations (32) and (35) with substituting the collective optimal harvest, H_{11}^*, we get

$$h_1^{j*} = \left[\left(1 - Z \frac{P}{(n+2)^2 \alpha}\right)\left(1 - \Gamma \frac{n+1}{n+2} \frac{P}{\alpha}\right) + \Gamma \right] \frac{P}{(n+2)\alpha} S_1. \tag{36}$$

Finally, by substituting the subgame perfect equilibrium in equation (35) and its collective level, $H_{11}^* (= \sum h_{11}^{j*})$, into the objective function in equation (34), we can derive the two-period optimal value function for each harvester:

$$V_{11}^{j*} = \left[(n+2)\Omega - (n+1)\Omega^2 + Z \left(1 - \Omega \frac{n+1}{n+2} \frac{P}{\alpha}\right) + r\beta X \right] \cdot \frac{P^2}{(n+2)^2 \alpha} S_1; \quad j = 1, 2, \ldots, n+1. \tag{37}$$

In the bracket, the first and second term show the parts of resource rents from period 1, and the third and last term present the parts from period 2.

The Effect of an EEZ

To examine how the existence of an EEZ affects the equilibrium harvest level and resource rent(s) generated from an HMFS fishery, we compare the Stackelberg and Cournot solutions. Recall that the Stackelberg model represents an HMFS fishery with an EEZ (*i.e.*, one coastal state and several DWF harvesters) and the Cournot model represents an HMFS fishery without an EEZ (*i.e.*, several symmetric harvesters).

To compare the total equilibrium harvest level and total resource rent with and without an EEZ (*i.e.*, the Stackelberg and Cournot models, respectively), we sum the relevant solution values for the $n + 1$ harvesters. We also compare these total equilibrium harvest and resource rent levels with the socially optimal levels (*i.e.*, the sole owner, cooperative fishery).

The total equilibrium harvest level in the first period for the Stackelberg model, denoted as H_s, is found by summing the equilibrium harvest levels for the $n + 1$ harvesters given in equation (18):

$$H_S = \left[\frac{1}{2} \Psi + \frac{n}{n+1} \Phi \left(1 - \Psi \frac{P}{2\alpha}\right) \right] \frac{P}{\alpha} S_1. \tag{38}$$

Adding the two-period optimal value function for the coastal state in equation (19) and n times the DWF harvester's function in equation (20), the total resource rent for the Stackelberg model, denoted as V_S, is

$$V_S = \left[\frac{1}{4}\left(2\Psi - \Psi^2\right) + \frac{n}{(n+1)^2}\left\{(n+1)\Phi - n\Phi^2\right\}\left(1 - \Psi\frac{P}{2\alpha}\right)\right. \tag{39}$$

$$\left. + \left\{\frac{1}{4} + \frac{1}{(n+1)^2}\left(1 - \frac{P}{2\alpha}\right)\right\}\left\{r\beta + \beta\left(1 - \Psi\frac{P}{2\alpha}\right)\left(1 - \Phi\frac{nP}{(n+1)\alpha}\right)\right\}\right]\frac{P^2}{\alpha}S_1.$$

The total equilibrium harvest level for the Cournot model, denoted as H_C, is derived by multiplying $n + 1$ to the individual equilibrium harvest level in equation (36):

$$H_C = \left[\left(1 - Z\frac{P}{(n+2)^2\alpha}\right)\left(1 - \Gamma\frac{n+1}{n+2}\frac{P}{\alpha}\right) + \Gamma\right]\frac{n+1}{n+2}\frac{P}{\alpha}S_1. \tag{40}$$

Also, by multiplying $n + 1$ to the two-period optimal value function in (37), the total resource rent for the Cournot model, denoted as V_C, is

$$V_C = \left[(n+2)\Omega - (n+1)\Omega^2 + Z\left(1 - \Omega\frac{n+1}{n+2}\frac{P}{\alpha}\right) + r\beta X\right]\frac{n+1}{(n+2)^2}\frac{P^2}{\alpha}S_1. \tag{41}$$

The socially optimal harvest level and resource rent are obtained if an HMFS is harvested by a sole owner (or as a cooperative fishery). By substituting $n = 0$ into the total equilibrium harvest level for the Cournot model in equation (40), which implies that there is sole access to the fishery, and further manipulating the equation, the socially optimal harvest level (denoted as H_{SO}) is

$$H_{SO} = \left[1 + \left(1 - \Pi\frac{P}{2\alpha}\right)\left(1 - \Pi\frac{P}{4\alpha}\right)\right]\Pi\frac{P}{2\alpha}S_1 \tag{42}$$

where

$$\Pi = 1 - \left[1 + \left(1 - \frac{P}{4\alpha}\right)^2\right]\frac{\beta P}{4\alpha} \quad \text{and} \quad \frac{39}{64} < \Pi < 1.$$

Also, by substituting $n = 0$ into the total resource rent for the Cournot model in equation (41) and manipulating the equation, the socially optimal resource rent (denoted as V_{SO}) is

$$V_{SO} = \left[2\Pi^2\left\{1 - \Pi\left(1 - \Pi\frac{P}{8\alpha}\right)\frac{P}{4\alpha}\right\} + \beta(1+r)\left\{1 + \left(1 - \frac{P}{4\alpha}\right)^2\right\}\right]\frac{P^2}{4\alpha}S_1. \tag{43}$$

Figure 1 shows the graphs of the total equilibrium harvest levels for three cases:

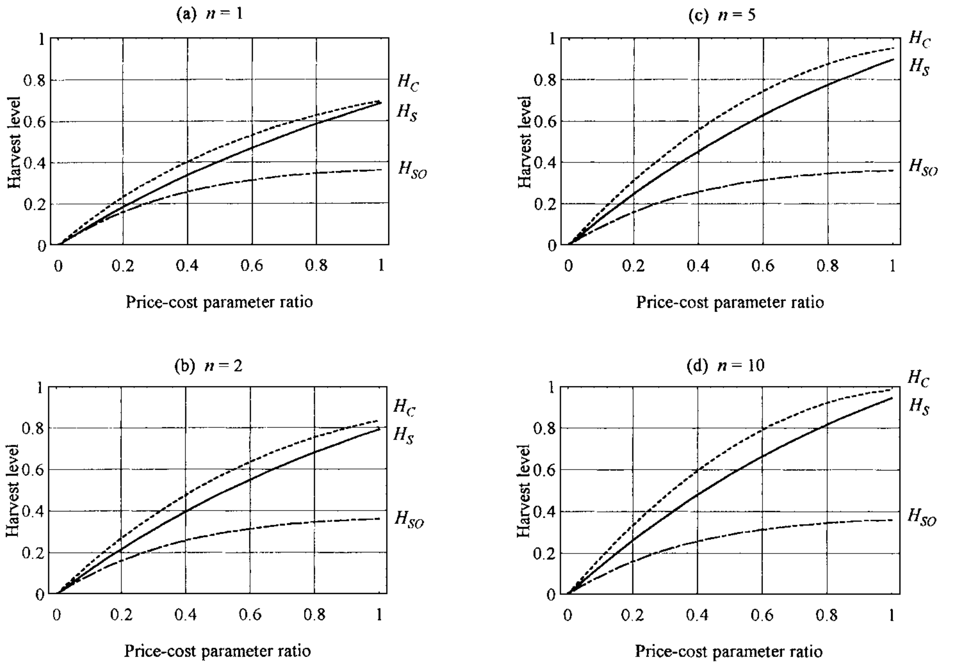

Figure 1. Total Equilibrium Harvest Levels for the Stackelberg Model (H_S), Cournot Model (H_C), and Social Optimal Harvest Level (H_{SO})

the Stackelberg model in equation (38), the Cournot model in equation (40), and the social optimal level in equation (42). These three levels are also depicted over a range of the price-cost parameter ratio (P/α) and shown for the different cases of the number of DWF harvesters (n = 1, 2, 5, and 10). We use the following parameter values: $\beta = 0.9$, $r = 0.5$, $S_1 = 1$, and $P = 1$. These graphs clearly indicate that the total equilibrium harvest level in the Cournot model is greater than that in the Stackelberg model and both are greater than the socially optimal harvest level.

In figure 2, we show the graphs of the total resource rent levels for three cases: the Stackelberg model in equation (39), the Cournot model in equation (41), and the social optimal level in equation (43). These graphs also indicate that the total resource rent in the Stackelberg model is greater than that in the Cournot model but both are less than the socially optimal resource rent level. Also, both figures 1 and 2 show that the greater the number of harvesters, the greater is the difference among three curves.

These results suggest the following remark: *An EEZ on an HMFS fishery reduces total equilibrium harvest and improves total welfare (i.e., total resource rent). Moreover, the improvement in total welfare with an EEZ is greater with a greater number of DWF harvesters.*

The economic intuition behind this remark is the following. Under an EEZ, only one state (the coastal state) can harvest a fish stock in the first stage in each period. Hence, in the first stage, the per unit harvesting cost is lower, and rent is higher, than for the case without an EEZ. In the second stage, the stock level is higher, which reduces harvest costs, as compared to the non-EEZ case. Note that this allows the DWF harvesters to earn higher rents in the second stage. It is interesting to note

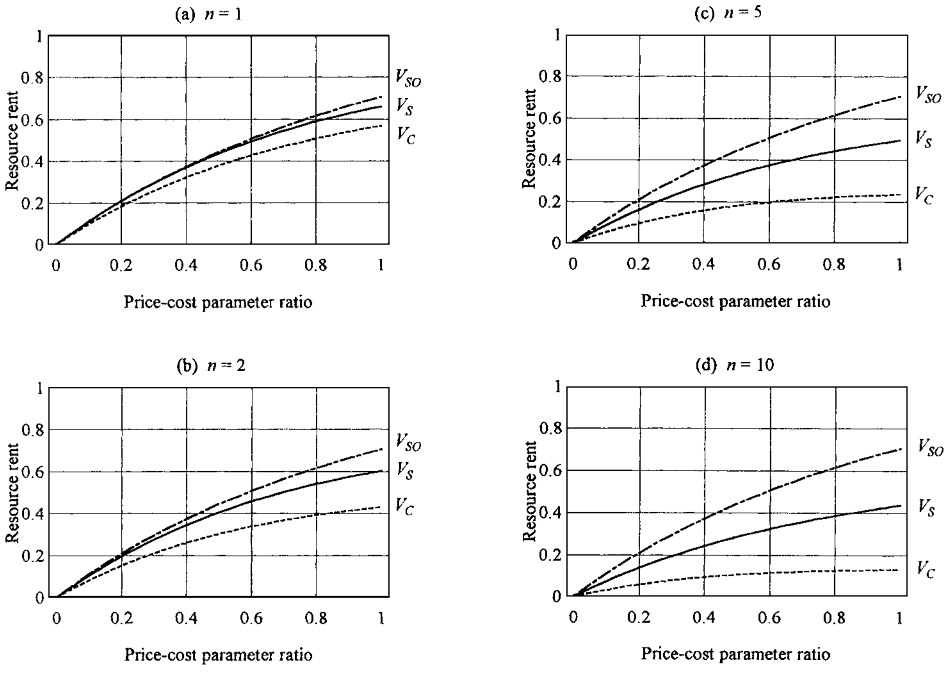

Figure 2. Total Resource Rents for the Stackelberg Model (V_S), Cournot Model (V_C), and Social Optimal Harvest Rent (V_{SO})

that even though total harvest does not differ much between the Stackelberg and Cournot cases, total resource rents do. Rents are significantly higher in the Stackelberg case because harvest costs fall in both stages 1 and 2. More than 50% of the rent loss in the Cournot case is erased by allowing an EEZ. However, equilibrium harvest levels are lower in stage 1 but higher in stage 2 in Stackelberg as compared to Cournot, leading to only a slight overall reduction in harvest with an EEZ.

Conclusion

This paper developed a two-period dynamic game model for examining an HMFS fishery. The model contains two stages in each period, in which the coastal state harvests the fish stock prior to any DWF harvesters. We solved the model for a subgame perfect equilibrium and derived equilibrium harvest levels and resource rents. We used the results to examine the effects of a change in the number of DWF harvesters and the effects of having an EEZ.

A change in the number of DWF harvesters in an HMFS fishery reduces total resource rents and increases the total equilibrium harvest level; harvest by the coastal state and the collective DWF harvesters increases, but the harvest level of the individual DWF harvester is reduced. In open-access bionomic equilibrium, the coastal state earns a positive resource rent, but the rents for the DWF harvesters is totally dissipated. In contrast, a Cournot model of common property resources find that all resource rents are totally dissipated (Negri 1990).

The existence of an EEZ results in much higher total welfare (*i.e.*, resource rents) with slightly decreased total equilibrium harvest levels as compared to the case without an EEZ. This result contrasts with Levhari and Mirman (1980) who show that sequential harvest (Stackelberg) yields greater equilibrium harvests, given the stock size, than does simultaneous harvest (Cournot). Our result differs because the switch to the Stackelberg model reduces the number of harvesters at the first stage. The reduction in harvesters dominates the strategic effect due to the sequential motive of harvest. In addition, the degree of the total welfare improvement by instituting an EEZ increases as the number of harvesters in an HMFS fishery increases. These results show that an EEZ, though not a perfect policy instrument, can increase rents from a fishery even though the fish stock may migrate into open water.

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Appendix

Proof of Proposition 1

Consider first the partial derivative of Φ in equation (14) and Ψ in equation (17) with respect to a parameter *n* (the number of DWF harvesters). We can show their signs as follows:

$$\frac{\partial \Phi}{\partial n} = \left(1 - \frac{P}{2\alpha}\right)\frac{2\beta P}{(n+1)^3\alpha} > 0 \tag{A1}$$

$$\frac{\partial \Psi}{\partial n} = \left[\frac{n}{n+1}\frac{\partial \Phi}{\partial n} + \frac{\Phi}{(n+1)^2}\right]\frac{\beta P^2}{4\alpha^2} > 0\,. \tag{A2}$$

Further, we can show

$$\frac{\partial(\Phi/n+1)}{\partial n} = -\frac{1}{(n+1)^2}\left[1 - \frac{3\beta P}{(n+1)^2\alpha}\left(1 - \frac{P}{2\alpha}\right)\right] < 0\,. \tag{A3}$$

Then, by using equation (A2), we can show the signs of the partial derivatives of the equilibrium harvest level with respect to n for the coastal state

$$\frac{\partial h_1^{1*}}{\partial n} = \frac{\partial \Psi}{\partial n} \frac{P}{2\alpha} S_1 > 0 \tag{A4}$$

and, by using equations (A2) and (A3), for the DWF harvesters

$$\frac{\partial h_1^{i*}}{\partial n} = \left[\left(1 - \Psi \frac{P}{2\alpha}\right) \frac{\partial(\Phi/n + 1)}{\partial n} - \frac{\Phi}{n+1} \frac{\partial \Psi}{\partial n} \frac{P}{2\alpha}\right] \frac{P}{\alpha} S_1 < 0 \tag{A5}$$

since both terms in the brackets are negative [note that, $73/128 < (1 - \Psi P/2\alpha) < 1$].

On the other hand, the partial derivative of the equilibrium harvest for the collective DWF harvesters with respect to the parameter n is

$$\frac{\partial H_1^{\sim 1*}}{\partial n} = \frac{\partial (n h_1^{i*})}{\partial n} = \left[\frac{n}{n+1}\left(1 - \Psi \frac{P}{2\alpha}\right)\frac{\partial \Phi}{\partial n} + \frac{\Phi}{(n+1)^2}\left(1 - \Psi \frac{P}{2\alpha}\right) - \frac{n}{n+1} \Phi \frac{\partial \Psi}{\partial n} \frac{P}{2\alpha}\right] \frac{P}{\alpha} S_1.$$

Substituting equation (A2) into this equation gives

$$\frac{\partial H_1^{\sim 1*}}{\partial n} = \left[\left\{\frac{n}{n+1} \frac{\partial \Phi}{\partial n} + \frac{\Phi}{(n+1)^2}\right\}\left(1 - \Psi \frac{P}{2\alpha}\right) - \frac{n}{n+1} \Phi \frac{\beta P^3}{8\alpha^3}\left\{\frac{n}{n+1}\frac{\partial \Phi}{\partial n} + \frac{\Phi}{(n+1)^2}\right\}\right] \frac{P}{\alpha} S_1 \tag{A6}$$

$$= \left\{\frac{n}{n+1} \frac{\partial \Phi}{\partial n} + \frac{\Phi}{(n+1)^2}\right\}\left[\left(1 - \Psi \frac{P}{2\alpha}\right) - \frac{n}{n+1} \Phi \frac{\beta P^3}{8\alpha^3}\right] \frac{P}{\alpha} S_1.$$

We manipulate Ψ to get

$$-\frac{n}{n+1} \Phi \frac{\beta P^3}{8\alpha^3} = -\Psi \frac{P}{2\alpha} + \left(1 - \frac{\beta P}{4\alpha}\right) \frac{P}{2\alpha}. \tag{A7}$$

Then, by substituting equation (A7) into equation (A6), we finally show

$$\frac{\partial H_1^{\sim 1*}}{\partial n} = \left\{\frac{n}{n+1} \frac{\partial \Phi}{\partial n} + \frac{\Phi}{(n+1)^2}\right\}\left[\left(1 - \Psi \frac{P}{2\alpha}\right) + \left(1 - \frac{\beta P}{4\alpha}\right) \frac{P}{2\alpha}\right] \frac{P}{\alpha} S_1 > 0 \tag{A8}$$

since all terms in the equation are positive. By equations (A4), (A5), and (A8), proposition 1 holds.

Proof of Proposition 2

Taking the partial derivative of the two-period optimal value function for the coastal state in equation (19) with respect to the parameter n, we can show its sign as

$$\frac{\partial V_1^{1*}}{\partial n} = \left[2\frac{\partial \Psi}{\partial n} - 2\Psi \frac{\partial \Psi}{\partial n} - \left(1 - \Psi \frac{P}{2\alpha}\right)\frac{\partial(\Phi n/n+1)}{\partial n} \frac{\beta P}{\alpha} - \left(1 - \Phi \frac{nP}{(n+1)\alpha}\right)\frac{\partial \Psi}{\partial n} \frac{\beta P}{2\alpha}\right] \frac{P^2}{4\alpha} S_1 \tag{A9}$$

$$= \left[2\,(\Psi - \Psi)\,\frac{\partial \Psi}{\partial n} - \left\{ \frac{n}{n+1}\,\frac{\partial \Phi}{\partial n} + \frac{\Phi}{(n+1)^2} \right\} \left(1 - \Psi\,\frac{P}{2\alpha} \right) \frac{\beta P}{\alpha} \right] \frac{P^2}{4\alpha}\, S_1$$

$$= -\left\{ \frac{\partial \Phi}{\partial n}\,\frac{n}{n+1} + \frac{\Phi}{(n+1)^2} \right\} \left(1 - \Psi\,\frac{P}{2\alpha} \right) \frac{\beta P^3}{4\alpha^2}\, S_1 < 0$$

since the inside of braces are positive by equation (A1).

To show the sign of the partial derivative of the two-period optimal value function for the DWF harvesters in equation (20), for simplicity, we first let

$$A \equiv \left[\left\{ (n+1)\Phi - n\Phi^2 \right\} \left(1 - \Psi\frac{P}{2\alpha} \right) + r\beta \left(1 - \frac{P}{2\alpha} \right) + \beta \left(1 - \Phi\frac{nP}{(n+1)\alpha} \right) \left(1 - \frac{P}{2\alpha} \right) \left(1 - \Psi\frac{P}{2\alpha} \right) \right]$$

so that the two-period optimal value function for the DWF harvesters is

$$V_1^{i*} = A\,\frac{P^2}{(n+1)^2\,\alpha}\,S_1 . \tag{A10}$$

Then, taking the partial derivative of equation (A10) with respect to n gives

$$\frac{\partial V_1^{i*}}{\partial n} = \frac{\partial A}{\partial n}\,\frac{P^2}{(n+1)^2\,\alpha}\,S_1 - A\,\frac{2P^2}{(n+1)^3\,\alpha}\,S_1 . \tag{A11}$$

We consider only the sign of the partial derivative of A with respect to n in equation (A11) since the second term is negative. Taking the partial derivative of A with respect to n, we get

$$\frac{\partial A}{\partial n} = \left[\frac{\partial}{\partial n} \left\{ (n+1)\Phi - n\Phi^2 \right\} \right] \left(1 - \Psi\frac{P}{2\alpha} \right) + \beta \left[\frac{\partial}{\partial n} \left\{ 1 - \Phi\frac{nP}{(n+1)\alpha} \right\} \right] \left(1 - \frac{P}{2\alpha} \right) \left(1 - \Psi\frac{P}{2\alpha} \right) \tag{A12}$$

$$- \left\{ (n+1)\Phi - n\Phi^2 \right\} \frac{\partial \Psi}{\partial n}\,\frac{P}{2\alpha} - \frac{\partial \Psi}{\partial n} \left(1 - \frac{P}{2\alpha} \right) \left(1 - \Psi\,\frac{P}{2\alpha} \right) \frac{\beta P}{2\alpha} .$$

Since the third and last terms are negative by equation (A2), we consider only the signs of the first and second terms. Manipulating these two terms and using equation (A2), we can show they are nonpositive.

$$\left[\frac{\partial}{\partial n} \left\{ (n+1)\Phi - n\Phi^2 \right\} \right] \left(1 - \Psi\,\frac{P}{2\alpha} \right) + \beta \left[\frac{\partial}{\partial n} \left(1 - \Phi\,\frac{nP}{(n+1)\alpha} \right) \right] \left(1 - \frac{P}{2\alpha} \right) \left(1 - \Psi\,\frac{P}{2\alpha} \right) \tag{A13}$$

$$= \left[\Phi - \Phi^2 + \left\{ n + 1 - 2n\Phi - \frac{n\beta P}{(n+1)\alpha} \left(1 - \frac{P}{2\alpha} \right) \right\} \frac{\partial \Phi}{\partial n} - \frac{\Phi}{(n+1)^2} \left(1 - \frac{P}{2\alpha} \right) \frac{\beta P}{\alpha} \right] \left(1 - \Psi\,\frac{P}{2\alpha} \right)$$

$$= \left[\Phi \left\{ 1 - \frac{1}{(n+1)^2} \left(1 - \frac{P}{2\alpha} \right) \frac{\beta P}{\alpha} \right\} - \Phi^2 + \left\{ n + 1 - 2n\Phi - \left(1 - \frac{P}{2\alpha} \right) \frac{n\beta P}{(n+1)\alpha} \right\} \frac{\partial \Phi}{\partial n} \right] \left(1 - \Psi\,\frac{P}{2\alpha} \right)$$

$$= \left[\Phi^2 - \Phi^2 + (n+1) \left\{ 1 - \left(1 - \frac{P}{2\alpha} \right) \frac{n\beta P}{(n+1)^2\,\alpha} - \left(1 - \frac{P}{2\alpha} \right) \frac{(n-1)\beta P}{(n+1)^2\,\alpha} - \Phi\,\frac{2n}{n+1} \right\} \frac{\partial \Phi}{\partial n} \right] \left(1 - \Psi\,\frac{P}{2\alpha} \right)$$

$$= -(n-1)\frac{\partial \Phi}{\partial n}\left[\Phi + \left(1 - \frac{P}{2\alpha}\right)\frac{\beta P}{(n+1)\alpha}\right]\left(1 - \Psi\frac{P}{2\alpha}\right) \leq 0$$

where the equality holds as $n = 1$. By equations (A11), (A12), and (A13), therefore, we can show

$$\frac{\partial V_1^{i*}}{\partial n} < 0. \tag{A14}$$

Hence, by equations (A9) and (A14), proposition 2 holds.

Proof of Proposition 3

We have already shown the bionomic equilibrium harvest level for the coastal state in section 3, which is a positive value. Now, we show that for DWF harvesters. First, taking the limit on n for Φ, we have

$$\lim_{n\to\infty}\Phi = 1 - \lim_{n\to\infty}\left\{\frac{1}{(n+1)^2}\right\}\left(1 - \frac{P}{2\alpha}\right)\frac{\beta P}{\alpha} = 1. \tag{A15}$$

Manipulating the one-period optimal value function for DWF harvesters in equation (20) gives

$$V_1^{i*} = \left[\frac{1}{n+1}\Phi - \frac{n}{(n+1)^2}\Phi^2 + \frac{r\beta}{(n+1)^2}\left(1 - \frac{P}{2\alpha}\right)\Big/\left(1 - \Psi\frac{P}{2\alpha}\right)\right. \tag{A16}$$
$$\left. + \frac{\beta}{(n+1)^2}\left(1 - \Phi\frac{nP}{(n+1)\alpha}\right)\left(1 - \frac{P}{2\alpha}\right)\right]\left(1 - \Psi\frac{P}{2\alpha}\right)\frac{P^2}{\alpha}S_1.$$

Then, by taking the limit on n for equation (A16) and using (A15), we can show

$$\lim_{n\to\infty}V_1^{i*} = \left[0\cdot 1 - 0\cdot 1^2 + 0\cdot r\beta\left(1 - \frac{P}{2\alpha}\right)\Big/\left(1 - \Sigma\frac{P}{2\alpha}\right)\right. \tag{A17}$$
$$\left. + 0\cdot\beta\left(1 - 1\cdot 1\cdot\frac{P}{\alpha}\right)\left(1 - \frac{P}{2\alpha}\right)\right]\left(1 - \Psi\frac{P}{2\alpha}\right)\frac{P^2}{\alpha}S_1 = 0$$

which completes the proof of proposition 3.