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This dissertation contains theoretical and empirical analyses on common property fisheries resources. The theoretical analysis focuses on a highly migratory fish stocks (HMFS) fishery, and examines the inefficiency caused by non-cooperative harvest. The empirical analysis focuses on a high seas fishery and conducts an empirical test on the effects of the current and future number of harvesters on equilibrium harvest and resource rents.

In the theoretical analysis, a two period, non-cooperative, game-theoretic model is developed for an HMFS fishery. In each period, the fish stock migrate from the exclusive economic zone (EEZ) of a coastal state into the high seas, where distant-water fishing (DWF) harvesters may harvest them. It is shown that having an EEZ improves total welfare by reducing total harvest and the degree of the welfare improvement increases when the number of harvesters in an HMFS fishery increases. It is also shown that new entrants to an HMFS fishery lead 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.

In the empirical analysis, a dynamic Cournot model is used to predict the strategic behavior of harvesters engaged in a non-cooperative fishery on a common property resource. The model predicts that an increase in the current number of harvesters in a common property fishery will increase the collective equilibrium harvest level, but will reduce both the equilibrium harvest level and the current resource rent for the individual harvester. Also, an increase in the future number of harvesters increases all three equilibrium levels. These predictions are tested using data from the Japanese trawl fishery in the Bering Sea Donut Hole. The empirical results on the effect of changes in the current and future numbers of harvesters on the collective and individual harvest rates and resource rents are consistent with theory.

Common Property Fisheries Resources:
A Game Theoretic and Empirical Analysis

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COMMON PROPERTY FISHERIES RESOURCES: A GAME THEORETIC AND EMPIRICAL ANALYSIS

Chapter I

INTRODUCTION

"The tragedy of the commons" has been the subject of many studies in resource economics. These studies have demonstrated two main conclusions: i) non-cooperative harvest of common property resources results in a socially inefficient outcome (i.e., overharvesting) and ii) the degree of inefficiency depends crucially on the number of harvesters in the commons. The first conclusion is illustrated by the famous example of the "prisoner's dilemma" game. Suppose that there are two fishermen, instead of two prisoners, that harvest fish from a common stock. The two possible strategies for each fisherman are a high or low catch. If both fishermen choose the low catch, they get $3 each. If they both choose the high catch, the fish stock is overharvested and they each obtain $2. If one fisherman chooses high catch, and the other chooses low catch, the former receives $4 and the latter receives $1. Figure I.1 shows the payoff matrix for the prisoner's dilemma faced by the fishermen.

		Fisherman 2: Low catch	Fisherman 2: High catch
Fisherman 1	Low catch	3 , 3	1 , 4
	High catch	4 , 1	2 , 2

Figure I. 1 The fishermen game as a prisoner's dilemma game

Even though it would be better for both fishermen to operate with a low catch, it is individually advantageous for each of them to operate with a high catch (high catch strictly dominates low catch). The unique Nash equilibrium to this game is for both fishermen to choose high catch. Therefore, common property fisheries result in overharvesting that is socially inefficient. This example illustrates "the tragedy of the commons."

The second conclusion comes from the nature of common property resources. Common property can be distinguished from open access, in that the right of access to the resource is assigned to a limited group in a common property resource. On the other hand, in an open access resource, entry is available to anyone who wants to use the resource. Since common property fisheries resources are harvested by a limited group, each member of the group will interact strategically with the others. Therefore, the number of harvesters operating on common property resources is a crucial factor for the optimal choice of each harvester.

This dissertation addresses problems raised by common property fisheries resources. In particular, the effect of the number of harvesters on the degree of inefficiency of equilibrium harvests and resource rents is examined. In chapter III, this point is analyzed in the case of a highly migratory fish stocks (HMFS) fishery. For the HMFS fishery, a two-period noncooperative game-theoretic model is constructed. The model consists of two stages in each period. In the first stage, the fish stock is located in the exclusive economic zone (EEZ) of a coastal state. In the second stage, the fish stock migrate to the high seas and distant-water fishing (DWF) states simultaneously harvest from the remaining fish stock. This model is referred to a Stackelberg model with the coastal state acting as the Stackelberg leader. Most other game theoretic models of the fishery have been Cournot models in which all states act simultaneously. The model includes harvest costs that have increasing unit cost as the proportion of stock harvested increases. The model is solved for a subgame perfect equilibrium.

Using the equilibrium solution, the effect of having an EEZ on an HMFS fishery is examined by comparing two types of oligopoly models, namely: Stackelberg and Cournot. Without an EEZ, the coastal state and the DWF states simultaneously choose harvest levels in stage 1 and 2. It is shown that having EEZ in an HMFS fishery reduces total harvest level and improves total welfare (i.e., resource rents).

In addition, how an increase in the number of DWF states affects both the equilibrium harvest level and resource rents is examined. Increasing the number of DWF states reduces total rents and increases the total equilibrium harvest level; harvest by the coastal state and the collective DWF states increases but the harvest levels of the individual DWF states is reduced. Furthermore, a bionomic equilibrium (Gordon, 1954) of open-access in the second stage is analyzed. With a bionomic equilibrium, resource rent is totally dissipated for DWF states, 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).

Chapter IV performs an empirical test for harvesting behavior in common property fisheries resources. By using the dynamic Cournot model of Negri (1990), the strategic predictions of harvesting behaviors on a common property fishery are developed. In particular, predictions on the effect of changes in the current or future number of harvesters are developed. An increase in the current number of harvesters in a common property fishery increases the collective harvest level, but reduces both the individual harvest and current resource rent. On the other hand, an increase in the future number of harvesters in a common property fishery increases the collective and individual harvest, and the current rent. These predictions are tested using data from the Japanese trawl fishery, in which the pollock stock were harvested by numbers of distant-water fishing harvesters between 1982 and 1991. These results are the first empirical test of strategic behavior in a common property fishery (at least that the author is aware). The empirical results are consistent with the predictions on the effect of changes in the current number of harvesters on the harvest rate and resource rent.

This dissertation is organized as follows. Chapter II reviews the resource economics literature using game theoretic models on common property resources issues and summarizes the important findings of the studies. Chapter III presents a theoretical analysis on an HMFS fishery. Chapter IV discusses an empirical analysis on a common property fishery. Chapter V contains a summary and concluding remarks.

Chapter II

LITERATURE REVIEW

Common property resources are harvested by a limited number of harvesters, so that the actions of each harvester affects other harvesters' decision. Therefore, in general, to analyze problems of common property resources, game theoretic models have been utilized. This chapter reviews the various game theoretic models to analyze common property resources. The specific game theoretic models discussed are i) Cooperative game model, ii) Cournot model, and iii) Stackelberg model. The final section will look at some empirical studies on common property resources.

II. 1 Cooperative Game Model

A Nash cooperative game model [1] was first utilized by Munro (1979 and 1987) to analyze the problems of a transboundary or shared fish stock. He solved the model for an open-loop equilibrium for a shared stock fishery by two coastal states, and showed that the cooperative solution is socially optimal if a side or transfer payment is possible (i.e., a binding agreement exists). Later, Vislie (1987) developed the dynamic version of Munro's model. He derived a subgame perfect equilibrium by constructing the two-period model

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[1] For the discussion of Nash cooperative game model, see Intriligator (1971) pp. 123-30.

and demonstrated the difference between the solution of open-loop (Nash) equilibrium and feedback (subgame perfect) equilibrium.

Recently, Missios and Plourde (1997) and Ferrara and Missios (1997) also used cooperative game models to analyze the case of transboundary fish stocks for two countries. Missios and Plourde incorporated a conservation motive for a coastal state into the cooperative model, and showed that a conservation motive for one or both countries increased the steady state fish stock level and that this level depended on the harvest share of the conservationist country. Ferrara and Missios developed the Vislie's model with differing breakdown payoffs between two countries and showed that the share for the country with the higher payoff in the second period was larger than fifty percent. They demonstrated that the prediction was consistent with the settlement in 1995 on the turbot war between Canada and the European Union (EU), in which Canada, much more conservationist than the EU, agreed to a share less than fifty percent for 1996.

The Nash cooperative game approaches, however, have some limitations. For example, Nash cooperative solution is an open-loop (Nash) equilibrium so that it exists only if a binding agreement on strategies is made among players at the outset of the game. For common property resources, especially in international fisheries, it may be difficult to have a binding agreement between countries due to lack of enforcement power.

II. 2 Cournot Model

II. 2. 1 Open-loop solutions

As a non-cooperative game, Cournot models have been utilized to analyze the problems of common property resources. The models were first solved for open-loop solutions as a static game model (Kemp and Long, 1980). The Cournot models were also used for demonstrating the difference between a open-loop and closed-loop (subgame perfect) solutions (McMillan and Sinn, 1980). Furthermore, Chiarella *et al.* (1984) and Kaitala *et al.* (1985) solved for an open-loop solution, and demonstrated conditions under which non-cooperative open-loop solutions coincide with cooperative ones. While the open-loop solutions have the limitation as mentioned in the previous section, Mohr (1988) asserted that an open-loop strategy can provide a more realistic (i.e., complex) model than a closed-loop strategy because it is easier to solve. He indeed used the open-loop equilibrium concept assuming a consistency rule that the length of the game is formalized.

The open-loop equilibrium solutions are, however, different from the closed-loop or feedback solutions (Eswaran and Lewis, 1985; Reinganum and Stokey, 1985). If a binding agreement does not exist, which is most likely in the case of straddling stocks and HMFS fisheries, it is appropriate to use a closed-loop or feedback solution concept, which is equivalent to a subgame perfect equilibrium.

II. 2. 2 Feedback solutions by dynamic programming

The dynamic Cournot game models are solved for a subgame perfect (feedback) equilibrium by dynamic programming (backwards induction). The notion of subgame perfect equilibrium was introduced by Selton (1965) as a Nash equilibrium in every subgame. That is, the subgame perfect equilibrium can eliminate Nash equilibria that rely on noncredible (or empty) threats. A pioneer work using the feedback equilibrium concept was by Levhari and Mirman (1980), who used a simple Cournot duopoly model with utility maximization (without market externality and extraction cost). They solved the model for a subgame perfect equilibrium on infinite-horizon and showed that Cournot duopoly fisheries result in a socially inefficient outcome.

On the other hand, the dynamic Cournot game model was used for analyzing nonrenewable resources. Eswaran and Lewis (1984) showed that the Cournot oligopoly extraction of oil seepage leads to a socially inefficient outcome. Using the same model, they also showed that the subgame perfect equilibrium and open-loop equilibrium were identical when the resource ownership was exclusive (Eswaran and Lewis, 1985). Reinganum and Stokey (1985) demonstrated that the period of commitment was important on the extraction of nonrenewable resources; shortening the period of commitment caused the rapid depletion of the resource. Each of these models included market externalities but not extraction costs.

Negri (1990) incorporated extraction cost in a dynamic Cournot model for an extraction of renewable common property resource with n harvesters. While his model did not include market externality, the inclusion of extraction cost allowed for the capture of both cost and stock externalities. The subgame perfect equilibrium on infinite-horizon derived from the model showed that the subgame perfect equilibrium was more socially inefficient than the open-loop equilibrium and, with open access, both equilibria lead to complete rent dissipation. Fischer and Mirman (1992 and 1996) studied the problem arising from the interaction of two species which were harvested by one of two countries (in 1992 paper) and by two countries (in 1996 paper), and showed that inclusion of biological externality to the model of Levhari and Mirman also resulted in a socially inefficient outcome.

Recently, the dynamic Cournot models were solved for a Markov perfect equilibrium to analyze the optimal number of firms in common property resources (Karp, 1992; Mason and Polasky, 1997). They examined the optimal numbers of firms allowed to harvest from the common property resource when firms possessed market powers in the output market.

II. 2. 3 Solutions by differential game

The subgame perfect equilibrium for the dynamic Cournot model can be derived by an another optimization method: differential game. Clark (1980) employed the differential game to analyze a shared stock fishery with *n* harvesters. His model was solved for a feedback equilibrium as the most rapid approach path and showed that the solution for a shared stock fishery with *n* harvesters resulted in a socially inefficient outcome. Plourde and Yeung (1989) also utilized a non-cooperative differential game with *n* harvesters and solved for a closed-loop equilibrium. They demonstrated that Cournot type fisheries with *n* harvesters lead to a socially inefficient outcome. Moreover, the differential games were used for studying a credible cooperative incentive equilibrium for a shared stock fishery with two harvesters (Kaitala and Pohjola, 1988; and Ehtamo and Hämäläinen, 1993).

The differential game, however, has difficulty in its computation and does not necessarily have solutions. Therefore, the differential game can be utilized only for the special models. The model by Clark employed a linear control problem so as to easily solve for a feedback equilibrium as the most rapid approach path. In the model by Plourde and Yeung, the open-loop and closed-loop equilibrium solutions coincided because of their logarithmic form of objective function.

II. 3 Stackelberg Model

Levhari and Mirman (1980) used a Stackelberg model and compared the Stackelberg with the Cournot model. In their duopoly model, each harvester harvested only once per period. They showed that sequential harvest (Stackelberg model) yielded greater equilibrium harvests, given the stock size, and smaller equilibrium steady state stock than did simultaneous harvest (Cournot model). As in the traditional Stackelberg model, there was a strategic effect for the leader to expand harvest in order to get the follower to contract harvest.

Kennedy (1987) considered a Stackelberg model for an HMFS fishery with two harvesters, which contained both market externality and constant unit harvesting cost.

However, he did not solve for a subgame perfect equilibrium, but instead performed a simulation that showed the gains for two states from Stackelberg type sequential harvest was socially inefficient and asymmetric for the two states.

Recently, a Stackelberg model was used for analyzing entry deterrence into a common property resource (Mason and Polasky, 1994). Their model including market cost and stock externalities was solved for a subgame perfect equilibrium. By using this model, Mason and Polasky analyzed conditions in which there was a fixed cost of entry and showed conditions under which the incumbent would deter or allow entry. They showed that potential entry increased the equilibrium harvest of the incumbent firm.

Without using a Stakelberg game model, there are some other approaches to analyze the problems of HMFS fisheries. Clarke and Munro (1987 and 1991) used a principal-agent model, in which a coastal state allows a DWF harvester to harvest by charging a fee, and analyzed the terms and conditions set by the coastal state for the DWF harvester to harvest within the EEZ. Kennedy and Pasternak (1991) developed a multicohort bioeconomic model to analyze the southern bluefin tuna fishery by two countries: Australia (coastal state) and Japan (DWF state). They used nonlinear programming to show that there was the potential gain of resource rents from a cooperative fishery instead of a Stackelberg type fishery. Hannesson (1997) used a repeated game for a common property fishery and examined the number of harvesters for realizing the cooperative fishery.

II. 4 Empirical Studies

While there are a number of theoretical studies of common property fisheries, there is a distinct lack of empirical work, which is largely because economic data on fisheries are generally not available. Previous empirical work testing game theoretic predictions for resource models have focused on non-common property nonrenewable resources. Griffin (1985) found evidence that weakly supported the hypothesis that OPEC behaved as a cartel and rejected other competing hypotheses for OPEC production behavior. Dahl and Yucel (1991) also found evidence that supported non-competitive behavior in oil markets both for OPEC and non-OPEC producers.

On the other hand, Polasky (1992) conducted an empirical analysis on common property nonrenewable resources (oil). He developed predictions of oil producer behavior using an oligopoly model and tested these predictions using oil industry data. He found evidence that supported the production behavior of oligopolists.

Chapter III

A THEORETICAL ANALYSIS OF A HIGHLY MIGRATORY FISH STOCKS FISHERY

III. 1 Introduction

There is great concern at present that fish stocks are being depleted by over-fishing. In part, over-fishing 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.[2] 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

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[2] 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 (1) within the Exclusive Economic Zone (EEZ) of two or more coastal states, or (2) both within the coastal state EEZ and the adjacent high seas.

members, non-NAFO countries enter the Grand Bank, which has caused international conflict (i.e., the Canada-Spain "turbot war").[3] In the Central Bering Sea, there is a pocket that is outside of both the United States and Russian EEZ (the Donut Hole). The groundfish in the Donut Hole are harvested by several DWF countries. In the middle of 1980's and early 1990's, DWF harvesters rapidly increased harvest of pollock from the Donut Hole, which is though 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 lifecycle both within and outside 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.

This chapter focus on the case of highly migratory fish stocks (HMFS). The consequences of non-cooperative management of an HMFS fishery is analyzed. Specifically, the following points are analyzed: (1) what effect does the existence of an EEZ have on non-cooperative management of an HMFS fishery; (2) how much does a non-cooperative equilibrium differ from the socially optimal outcome (i.e., a cooperative

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

management outcome); and (3) how does non-cooperative equilibrium change with a change in the number of DWF harvesters.

To answer these questions, a two-period non-cooperative game-theoretic model is constructed. 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. It is assumed that the government of the coastal state regulate the fishing activity within the EEZ to maximize results for the coastal state (i.e., they act as a single harvester).[4] 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. The model is solved for a feedback (subgame perfect) equilibrium.[5]

With an HMFS that begins the period in the coastal state EEZ, the coastal state harvesters can harvest the stock prior to DWF harvesters. This model is referred to 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, the results of the Stackelberg model are compared with the ones of a Cournot type model with no EEZ. In

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

[5] A feedback equilibrium is distinguished 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).

the Cournot model, the coastal state and DWF harvesters simultaneously choose harvest levels in stage one and two.[6] It is shown that having EEZ in an HMFS fishery, of the type modeled in this chapter, 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.

Also, the welfare consequences of instituting an EEZ in an HMFS fishery is examined. 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

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[6] The Cournot model, a simultaneous move game, has been utilized to show the inefficiency of non-cooperative fisheries (Levhari and Mirman, 1980; Fischer and Mirman, 1992 and 1996), and shows the difference between a feedback (subgame perfect) equilibrium and an open-loop (Nash) equilibrium (Eswaran and Lewis, 1984 and 1985; Reinganum and Stokey, 1985; Negri, 1990). Previously, several papers have solved for open-loop equilibrium (Chiarella et al., 1984; Kaitala et al., 1985; 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).

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, the Stackelberg model is used 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.[7] Also, a bionomic equilibrium (Gordon, 1954) of open-access in the second stage is analyzed. 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.

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[7] 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.

In the Stackelberg model, it is assumed 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). Considering the case where harvesters within the EEZ act non-cooperatively, it is shown that harvest within the coastal state increases and rents fall.

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

(1997) use cooperative game models to analyze the case of straddling fish stocks and HMFS. In our model, the socially optimal (cooperative) solution is also solved and the relative inefficiency of our non-cooperative solutions is shown.

This chapter is organized as follows. The following section constructs a model of an HMFS fishery and solves for a subgame perfect equilibrium. Section III. 3 analyzes the effect of entrants on the equilibrium harvest and resource rent. Section III. 4 derives a subgame perfect equilibrium in a Cournot model. In section III. 5, 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.

III. 2 The Stackelberg Model for an HMFS

Suppose there are n+1 harvesters including one coastal state and n symmetric DWF harvesters denoted as i = 1 and i = 2, 3, ⋯, n+1, respectively. Each harvester i chooses the harvest level h_t^i in period t, t = 1, 2. Within the coastal state, it is assumed 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).[8] Let S_t be the fish stock available for harvest at the beginning of period t.

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[8] Suppose the coastal government cannot regulate the coastal state fishing fleet, which consists of 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:

$$H_t = \sum_{k=1}^{m} h_t^k + \sum_{i=1}^{n} h_t^i = H_t^1 + H_t^{-1}; \quad t = 1, 2.$$

In each period, there are two stages. In the first stage, the fish stock, S_t, is 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 harvest level h_t^i (for i = 2, 3, ···, 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:

$$H_t = h_t^1 + \sum_{i=2}^{n+1} h_t^i = h_t^1 + H_t^{-1}; \quad t = 1, 2, \qquad \text{(III.1)}$$

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

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, it is assumed that stock

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

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

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

and for the n DWF harvesters change to:

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

where $\tilde{\Phi} = 1 - \left[1 - \frac{mP}{(m+1)\alpha}\right]\frac{\beta P}{(n+1)^2\alpha}$ 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.

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

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

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

It is assumed 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

$$C_t^1 = \alpha \frac{h_t^1}{S_t} h_t^1 \text{ and}$$

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

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 $0 < P < \alpha$.[9] Alternatively, we could assume that

[9] To get an interior solution for the subgame perfect equilibrium in the Stackelberg model, a condition needed is

$$0 < P < 2\alpha.$$

price is a linear function of the total harvest within a stage: $P(x_t) = a - x_t$, where x_t equals h_t^1 in stage one and x_t equals H_t^{-1} in stage two.[10] Assuming a downward sloping demand curve does not affect the positive analysis any differently than would making costs increasingly convex in current stage harvest. 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

$$\pi_t^1 = h_t^1\left(P - \alpha\frac{h_t^1}{S_t}\right) \text{ and}$$

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

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 III. 4, a condition needed is

$$0 < P < 3\alpha;$$

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 III. 3, further, a stronger assumption is necessary:

$$0 < P < \alpha,$$

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:

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

Therefore, the strongest assumption, $0 < P < \alpha$, is used for the price level in this chapter.

[10] 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. This effect is not analyzed in this study.

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, backward induction is used and begins 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:

$$\max_{h_2^i} \quad \pi_2^i(h_2^1, h_2^2, \cdots, h_2^{n+1})$$

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

Take the first order condition of (III.5) and set it equal to zero to find a typical harvester's best response function.[11] Sum over the *n* identical first-order conditions and solve it for the profit maximizing harvest level for each DWF harvester *i*:

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

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[11] 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:

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

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

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

In the Cournot model in section III. 4, the second-order conditions are also satisfied for a maximum by the same way. It also should be noted that there is 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 rivals' harvests (Tirole, p. 226).

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

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

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

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

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

$$\left(h_2^{1*}, h_2^{2*}(h_2^{1*}), \cdots, h_2^{n+1*}(h_2^{1*})\right)$$

$$= \left(\frac{P}{2\alpha}S_2, \left(1-\frac{P}{2\alpha}\right)\frac{P}{(n+1)\alpha}S_2, \cdots, \left(1-\frac{P}{2\alpha}\right)\frac{P}{(n+1)\alpha}S_2\right). \tag{III.9}$$

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 (III.9) into both the objective function of the coastal state in (III.7) and that of the n DWF harvesters in (III.5), the one-period optimal value function for the coastal state is

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

and for the n DWF harvesters is

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

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

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

$$\max_{h_1^i} \ \pi_1^i(h_1^1, h_1^2, \cdots, h_1^{n+1})$$

$$= \max_{h_1^i} \ h_1^i \left(P - \alpha \frac{H_1^{-1}}{S_1 - h_1^1} \right) + \beta \left[V_2^{i*}(S_2) \right]; \quad i = 2, 3, \cdots, n+1, \tag{III.12}$$

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 the future period (period 2) profit.

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

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

$$i = 2, 3, \cdots, n+1, \qquad \text{(III.13)}$$

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

$$h_1^{i*} = \Phi\frac{P}{(n+1)\alpha}(S_1 - h_1^1); \quad i = 2, 3, \cdots, n+1, \qquad \text{(III.14)}$$

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

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

$$\max_{h_1^1} \; \pi_1^1\left(h_1^1, h_1^2(h_1^1), \cdots, h_1^{n+1}(h_1^1)\right)$$

$$= \max_{h_1^1} \; h_1^1\left(P - \alpha\frac{h_1^1}{S_1}\right) + \beta\left[V_2^{1*}(S_2)\right]. \qquad \text{(III.15)}$$

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

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

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

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

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

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

$$\left(h_1^{1*}, h_1^{2*}(h_1^{1*}), \cdots, h_1^{n+1*}(h_1^{1*})\right)$$

$$= \left(\Psi \frac{P}{2\alpha} S_1, \Phi\left(1 - \Psi \frac{P}{2\alpha}\right)\frac{P}{(n+1)\alpha} S_1, \cdots, \Phi\left(1 - \Psi \frac{P}{2\alpha}\right)\frac{P}{(n+1)\alpha} S_1\right). \tag{III.18}$$

Note that the coastal state chooses to harvest a smaller proportion of stock in the first period than in the second (equation (III.9) times Ψ). Similarly, each DWF harvester chooses to harvest a smaller proportion of stock in the first period than in the second ($\Phi \cdot P/(n+1)\alpha < P/(n+1)\alpha$). These results occurs 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 first period, the coastal state can get the 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, the subgame perfect outcome in (III.18) is substituted into both the objective function for the coastal state in (III.16) and the objective function for the n DWF harvesters in (III.13). The following value functions are obtained for the coastal state,

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

and the DWF harvesters,

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

$$\left. + \beta\left(1 - \frac{P}{2\alpha}\right)\left(1 - \Psi\frac{P}{2\alpha}\right)\left(1 - \Phi\frac{nP}{(n+1)\alpha}\right)\right]\frac{P^2}{(n+1)^2\alpha}S_1; \quad i = 2, 3, \cdots, n+1. \quad \text{(III.20)}$$

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.

III. 3 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. Both a marginal increase in the number of DWF harvester and open access (bionomic) equilibrium are analyzed.

III. 3. 1 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 ($H_1^{\sim 1*} = n \cdot h_1^{i*}$) 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 A for proofs of all propositions).

Proposition III.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 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 period 1 and in period 2 than they are without the increase in the number of DWF harvesters.

Next, 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 is examined. 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 is summarized in the following proposition.

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

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 off 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.

III. 3. 2 Open Access Equilibrium

Next, open-access (bionomic) equilibrium (Gordon, 1954) is analyzed. 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 (III.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 (III.4) with $t = 1$):

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

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

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

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

These results are summarized in the following proposition.

Proposition III.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 ($P < \alpha$).

III. 4 The Cournot Model for an HMFS without an EEZ

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

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

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

$$C_{t1}^j = \alpha \frac{H_{t1}}{S_t} h_{t1}^j \text{ and}$$

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

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

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

$$\pi_{t2}^j = h_{t2}^j \left(P - \alpha \frac{H_{t2}}{S_t - H_{t1}} \right); \quad j = 1, 2, \cdots, n+1; \quad t = 1, 2. \tag{III.23}$$

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.

Backward induction is used to solve the 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:

$$\max_{h_{22}^j} \quad \pi_{22}^j(h_{22}^1, h_{22}^2, \cdots, h_{22}^{n+1})$$

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

Taking the first order condition of (III.24) and setting it equal to zero finds a typical harvester's best response function for each of the n+1 harvesters. The n+1 identical first-order conditions are summed over and solved for the optimal harvest level for each harvester j:

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

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 (III.24), the second stage value function for each harvester is found by substituting in the optimal harvest levels of the individual in equation (III.25) and its collective harvest level, $H_{22}^* (= \sum h_{22}^{j*})$:

$$V_{22}^{j*} = \frac{P^2}{(n+2)^2 \alpha}(S_2 - H_{21}); \quad j = 1, 2, \cdots, n+1. \qquad \text{(III.26)}$$

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

$$\max_{h_{21}^j} \quad \pi_{21}^j(h_{21}^1, h_{21}^2, \cdots, h_{21}^{n+1})$$

$$= \max_{h_{21}^j} \; h_{21}^j\left(P - \alpha\frac{H_{21}}{S_1}\right) + \left[V_{22}^{j*}\right]; \quad j = 1, 2, \cdots, n+1. \qquad \text{(III.27)}$$

Substituting the half-period optimal value function in (III.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

$$h_{21}^{j*} = \Lambda\frac{P}{(n+2)\alpha}S_1; \quad j = 1, 2, \cdots, n+1, \qquad \text{(III.28)}$$

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

Substituting the subgame perfect equilibrium in (III.28) and its collective harvest by all harvesters, $H_{21}^{*}(=\Sigma\, h_{21}^{j*})$, into the objective function in (III.27), the second period optimal value function for each harvester is

$$V_{21}^{j*}(S_2) = \mathrm{X}\frac{P^2}{(n+2)^2\alpha}S_2; \quad j = 1, 2, \cdots, n+1, \qquad \text{(III.29)}$$

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

Next, the first period is considered. By the backward induction, the problem for the n+1 harvesters at the second stage in period 1 can be written as

$$\max_{h_{12}^j} \; \pi_{12}^j(h_{12}^1, h_{12}^2, \cdots, h_{12}^{n+1})$$

$$= \max_{h_{12}^j} \; h_{12}^j\left(P - \alpha\frac{H_{12}}{S_1 - H_{11}}\right) + \beta\left[V_{22}^{j*}(S_2)\right]; \quad j = 1, 2, \cdots, n+1. \qquad \text{(III.30)}$$

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

$$\max_{h_{12}^j} \; h_{12}^j\left(P-\alpha\frac{H_{12}}{S_1-H_{11}}\right)+\mathrm{X}\frac{\beta P^2}{(n+2)^2\alpha}\left[(1+r)S_1-H_{11}-H_{12}\right];$$

$$j=1,2,\cdots,n+1. \qquad \text{(III.31)}$$

Finding the $n+1$ first-order conditions (best response function) for each of the $n+1$ harvesters and summing over finds the profit maximizing harvest level for each harvester at the second stage in period 1.

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

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

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

$$V_{12}^{j*}=\mathrm{Z}\frac{P^2}{(n+2)^2\alpha}(S_1-H_{11})+\mathrm{X}\frac{r\beta P^2}{(n+2)^2\alpha}S_1; \quad j=1,2,\cdots,n+1, \qquad \text{(III.33)}$$

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

Given the second stage solution, the problem for each harvester at the first stage in period 1 can be derived as

$$\max_{h_{11}^j} \; \pi_{11}^j(h_{11}^1,h_{11}^2,\cdots,h_{11}^{n+1})$$

$$= \max_{h_{11}^j} \; h_{11}^j\left(P-\alpha\frac{H_{11}}{S_1}\right)+\left[V_{12}^{j*}\right]; \quad j=1,2,\cdots,n+1. \qquad \text{(III.34)}$$

Substituting the one and half-period optimal value function in (III.33), the best response functions for each of the n+1 harvesters are found and these n+1 first-order conditions are summed over to find the profit maximizing harvest level for each harvesters at the first stage in period 1:

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

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

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

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

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

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

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

$$j = 1, 2, \cdots, n+1; \tag{III.37}$$

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.

III. 5 Effects 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, the Stackelberg and Cournot solutions are compared. 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), the relevant solution values for the n+1 harvesters are summed together. Also, these total equilibrium harvest and resource rent levels with the socially optimal levels (i.e., the sole owner, cooperative fishery) are compared.

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 (III.18):

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

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

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

$$+\left\{\frac{1}{4}+\frac{1}{(n+1)^2}\left(1-\frac{P}{2\alpha}\right)\right\}\left\{r\beta+\beta\left(1-\Psi\frac{P}{2\alpha}\right)\left(1-\Phi\frac{nP}{(n+1)\alpha}\right)\right\}\Bigg]\frac{P^2}{\alpha}S_1. \quad \text{(III.39)}$$

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 (III.36):

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

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

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

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 (III.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

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

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

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

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

Figure III.1 shows the graphs of the total equilibrium harvest levels for three cases: the Stackelberg model in (III.38), the Cournot model in (III.40), and the social optimal level in (III.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). The following parameter values are used: $\beta = 0.9$, $r = 0.5$, $S_1 = 1$, and $P = 1$. These graphs clearly indicate that the total equilibrium harvest level in Cournot model is greater than that in Stackelberg model and both are greater than the socially optimal harvest level.

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

These results suggest the following remark:

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.*

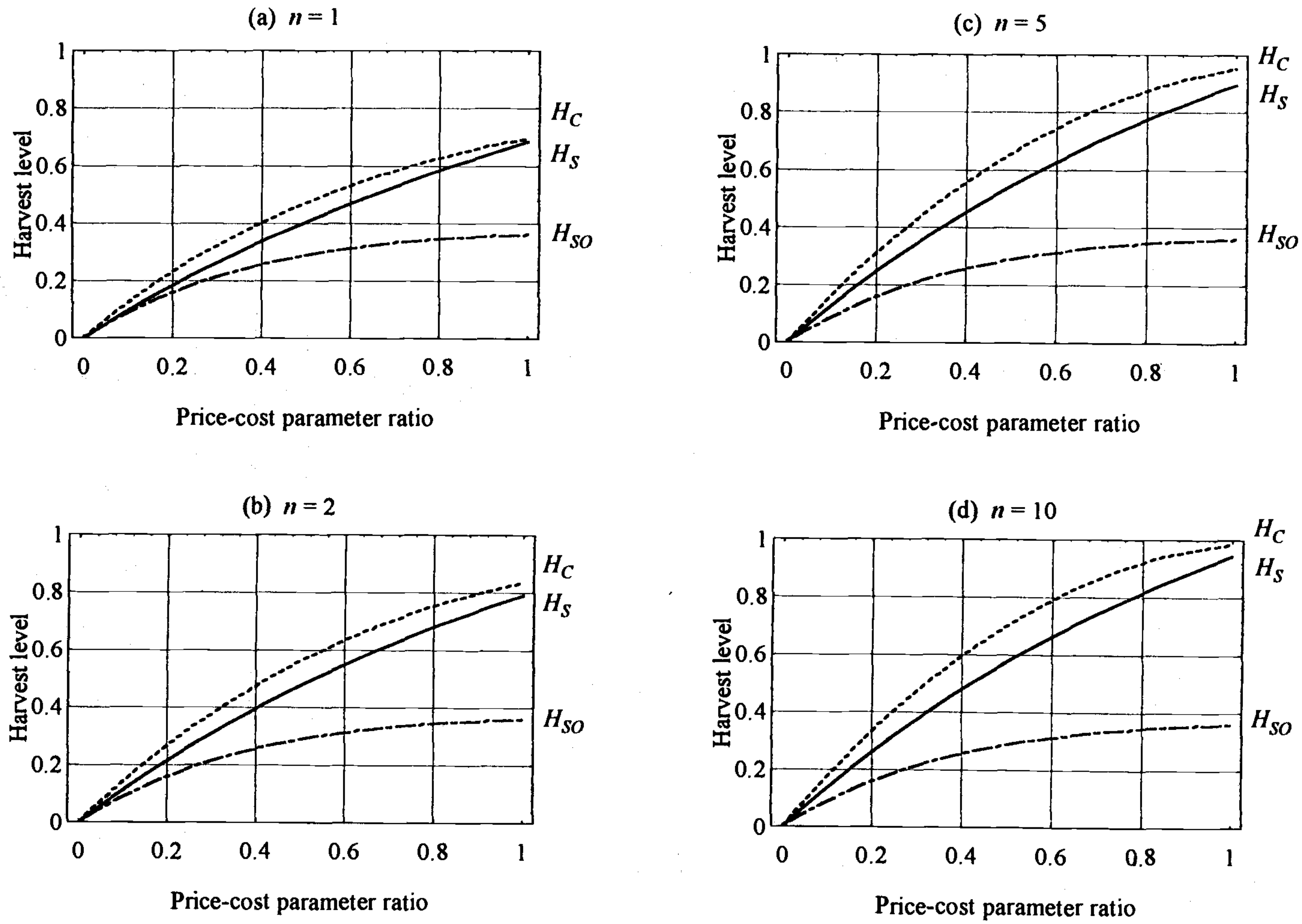

Figure III. 1 The total equilibrium harvest levels for the Stackelberg model (H_S) and the Cournot model (H_C), and the social optimal harvest level (H_{SO})

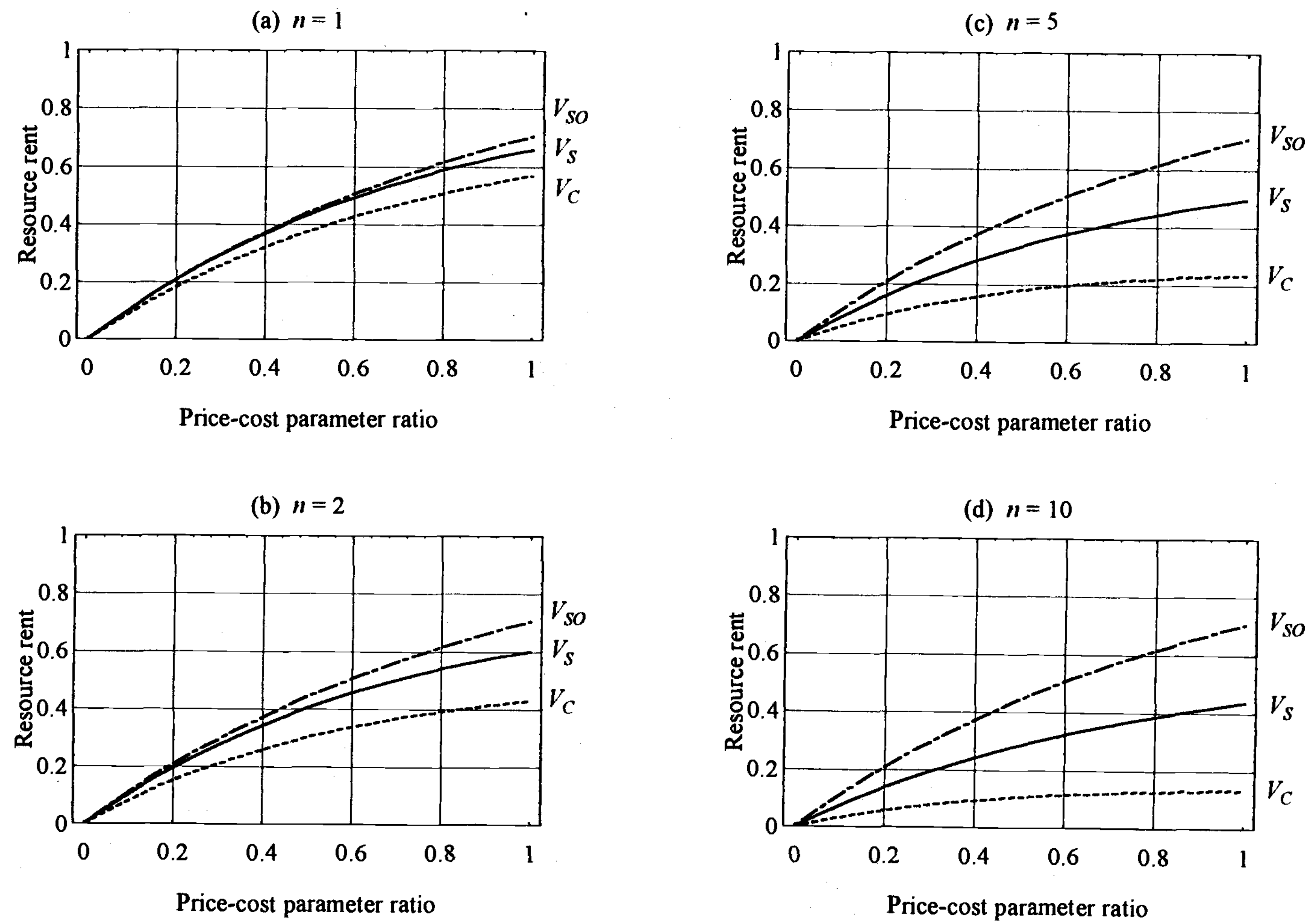

Figure III. 2 The total resource rents for the Stackelberg model (V_S) and the Cournot model (V_C), and the social optimal resource rent (V_{SO})

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 a higher rents in the second stage. It is interesting to note 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 stage 1 and stage 2. More than 50 % of the rent loss in the Cournot case is erased by allowing an EEZ. However, equilibrium harvests 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.

Chapter IV

AN EMPIRICAL ANALYSIS OF A HIGH SEAS FISHERY

IV. 1 Introduction

One of the fundamental insights from a game theoretic approach to common property resources is that the resource will be overharvested because each harvester considers only her own incentives, not the effect of her actions on the other harvesters. Furthermore, the degree of this overharvesting depends crucially on the number of harvesters in the commons. In this paper, the strategic predictions of harvesters on a common property fishery are developed by using the dynamic Cournot model of Negri (1990). This paper develops predictions on the effect of changes in the current or future number of harvesters. An increase in the current number of harvesters in a common property fishery increases the collective harvest level, but reduces both the individual harvest and current resource rent. On the other hand, an increase in the future number of harvesters in a common property fishery increases the collective and individual harvest, and the current rent. These predictions are tested using data from the Japanese trawl fishery, in which the pollock stock were harvested by numbers of distant-water fishing harvesters between 1982 and 1991. These results are the first empirical test of strategic behavior in a common property fishery (at least that the author is aware). The empirical results are consistent with the predictions on the effect of changes in the current number of harvesters, on the collective and individual harvest rates and individual current resource rent are consistent with theory.

In previous theoretical work, Levhari and Mirman (1980) first develop feedback dynamic Cournot and Stackelberg duopoly models. They solve for subgame perfect equilibrium in an infinite-horizon game, and show that Cournot and Stackelberg equilibrium lead to socially inefficient outcomes. Negri (1990) develops a dynamic Cournot model with *n* harvesters and with a harvest cost which increases with the ratio of harvest to stock. He solves for a subgame perfect equilibrium in an infinite-horizon and compares the subgame perfect equilibrium under different numbers of harvesters. He shows that with open access, the equilibrium leads to complete rent dissipation. Clark (1980) and Plourde and Yeung(1989) solve dynamic Cournot models with *n* harvesters by using a differential game. They also show that a common property fishery with *n* harvesters is socially inefficient. Recently, Naito and Polasky (1997) develop a dynamic Stackelberg model with *n* harvesters in the case of a highly migratory fish stocks (HMFS) fishery. They show that entry into an HMFS fishery reduces total resource rents and increases the total harvest. Karp (1992) and Mason and Polasky (1997) analyze the optimal numbers of firms to allow to harvest from the common property resource when firms possess market powers in the output market.

While there are a number of theoretical studies of common property fisheries, there is a distinct lack of empirical work, which is largely because economic data on fisheries are generally not available. Previous empirical work testing game theoretic predictions for resource models have focused on non-common property nonrenewable resources (Griffin, 1985; Dahl and Yucel, 1991; Polasky, 1992). The data used in this paper are published annually by the Japanese government. The data are for one of the Japanese trawlers groups, which is called the *Hokutensen*, operating in the Bering Sea. This data set includes detailed information on fishing cost and revenues. In the Central Bering Sea, there is a high seas pocket (the Donut Hole), which is a residual area outside both the United States and Russian exclusive economic zone (EEZ). The pollock stock in the Donut Hole (i.e., the Aleutian Basin stock) was intensively harvested by numbers of distant-water fishing (DWF) trawlers of five countries (Japan, China, South Korea, Poland, and Russia) between 1982 and 1991. While the high seas Donut Hole has the nature of open-access, in which anyone can enter, in fact, it has the nature of a common property resource because the high fixed cost of distant-water fishery limits the entry to only certain DWF trawlers. These DWF trawlers rapidly increased their numbers and total harvest of pollock from the Donut Hole in the middle of 1980's. Japanese trawlers were major harvesters of the pollock stock in the Donut Hole.

To test the predictions of the non-cooperative fishery in the Donut Hole, three equations of the collective and individual equilibrium harvest, and individual first-period profit (resource rent) are used. These equations include the current and future number of harvesters as explanatory variables. The parameters for the three equations are estimated by using equation-by-equation ordinary least squares (OLS) and three stage least squares (3SLS) techniques. The estimated parameters for the current number of harvesters are of the expected sign in all three equations and statistically significant for the collective harvest and individual current rent equations, but not for the individual harvest equation.

The estimated parameters for the future number of harvesters have the expected sign in all three equations and statistically significant for the collective harvest, but not for the individual harvest equation and the current rent equations. It should be noted, however, that these results are based on a very small sample size. Nevertheless, the basic conclusions remain robust with alternative estimation techniques and specifications.

This chapter is organized as follows. Section IV. 2 presents the background of the international and Japanese trawl fisheries in the Bering Sea Donut Hole. Section IV. 3 provides the two propositions for the strategic behavior of the common property harvesters by using the Cournot dynamic oligopoly model of Negri. Section IV. 4 presents empirical models and estimation techniques. Section IV. 5 explains the data used in this study. In section IV. 6, the results are reported. The final section discusses weakness in the data and an alternative explanation.

IV. 2 Background

IV. 2. 1 International trawl fisheries in the Bering Sea

The Bering Sea encompasses a total surface area of about 2.3 million square kilometers, and includes the Eastern and Western continental shelves, which has depths of 200 meters or less, and the central basin, which exceeds 2,000 meters in depth (see Figure IV.1). The Bering Sea fisheries constitute one of the most valuable fish resources in the world, and include many kinds of fish such as cod, sole, flounder, perch, mackerel,

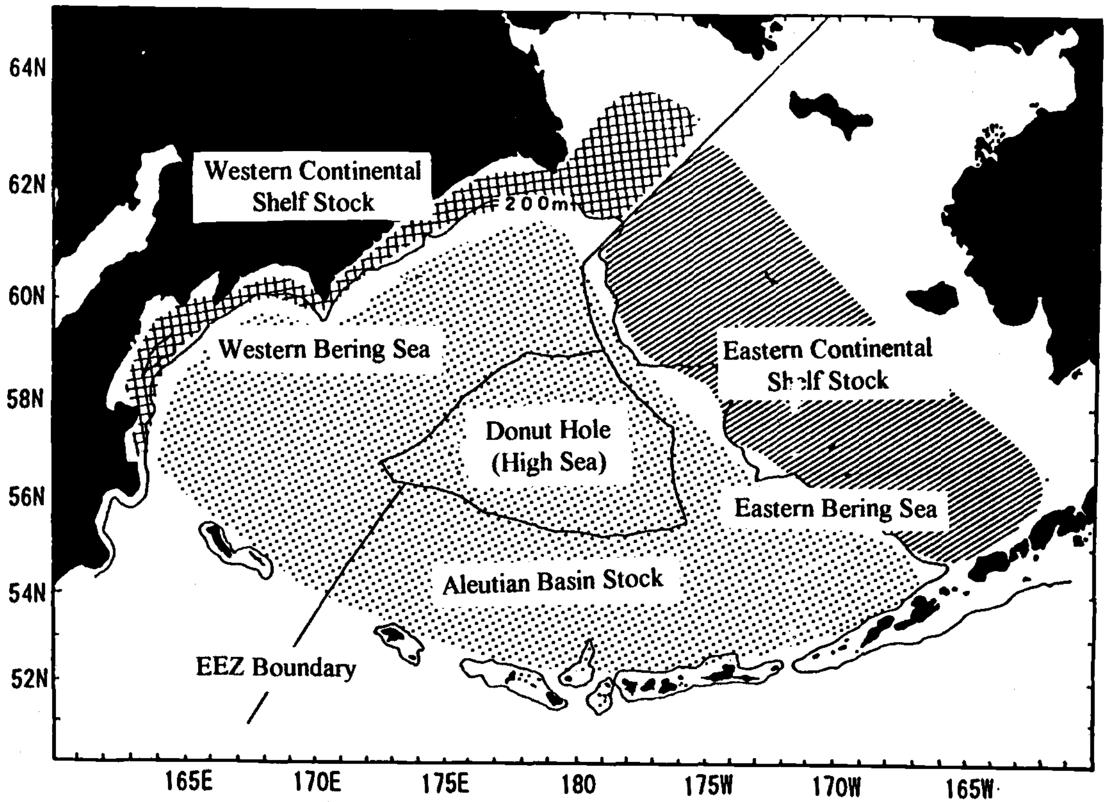

Figure IV. 1 Bering Sea Donut Hole and location of three pollock stocks.
Source: Adapted from Mito (1993).

lockington, rockfish, and pollock. With respect to Bering Sea pollock, there are three hypothetical pollock stocks: Eastern continental shelf, Western continental shelf, and Aleutian Basin stocks.

Figure IV.2 shows pollock catches from three areas in the Bering Sea from 1961 to 1992. In the Eastern Bering Sea, the harvest of pollock by Japanese DWF trawlers started in the early 1960's, while the harvest of flounder began in the mid 1950's. In 1972, the total pollock catches from the Eastern Bering Sea dramatically increased and reached a peak of 1.87 million metric tons. In 1977, the United States and the Soviet Union (now Russia) declared their 200-miles EEZ following the global trend of the "ocean enclosure movement" of the coastal states. The declarations of EEZ excluded foreign fishing fleets, but most DWF trawlers could continue to harvest pollock stock within the United States EEZ at quotas assigned through bilateral agreements between the United States and the DWF countries. As a collateral condition, Japan was required to buy the pollock harvested by U.S. trawlers. The quota set by the United States, however, has gradually declined following the development of the U.S. trawl fisheries in the Bering Sea, which was a consequence of the United States "Americanization" policy implicit in the Magnuson Fishery Conservation and Management Act of 1976.

The DWF trawlers which were excluded from the United States EEZ because of the reduction of the quota, turned to other harvesting possibilities, notably the newly discovered pollock stock in the high seas Donut Hole (i.e., the Aleutian Basin stock). This high seas Donut Hole encompasses approximately 48,000 square miles of surface area which is approximately 10 percent of the entire Bering Sea (see Figure IV.1). Later,

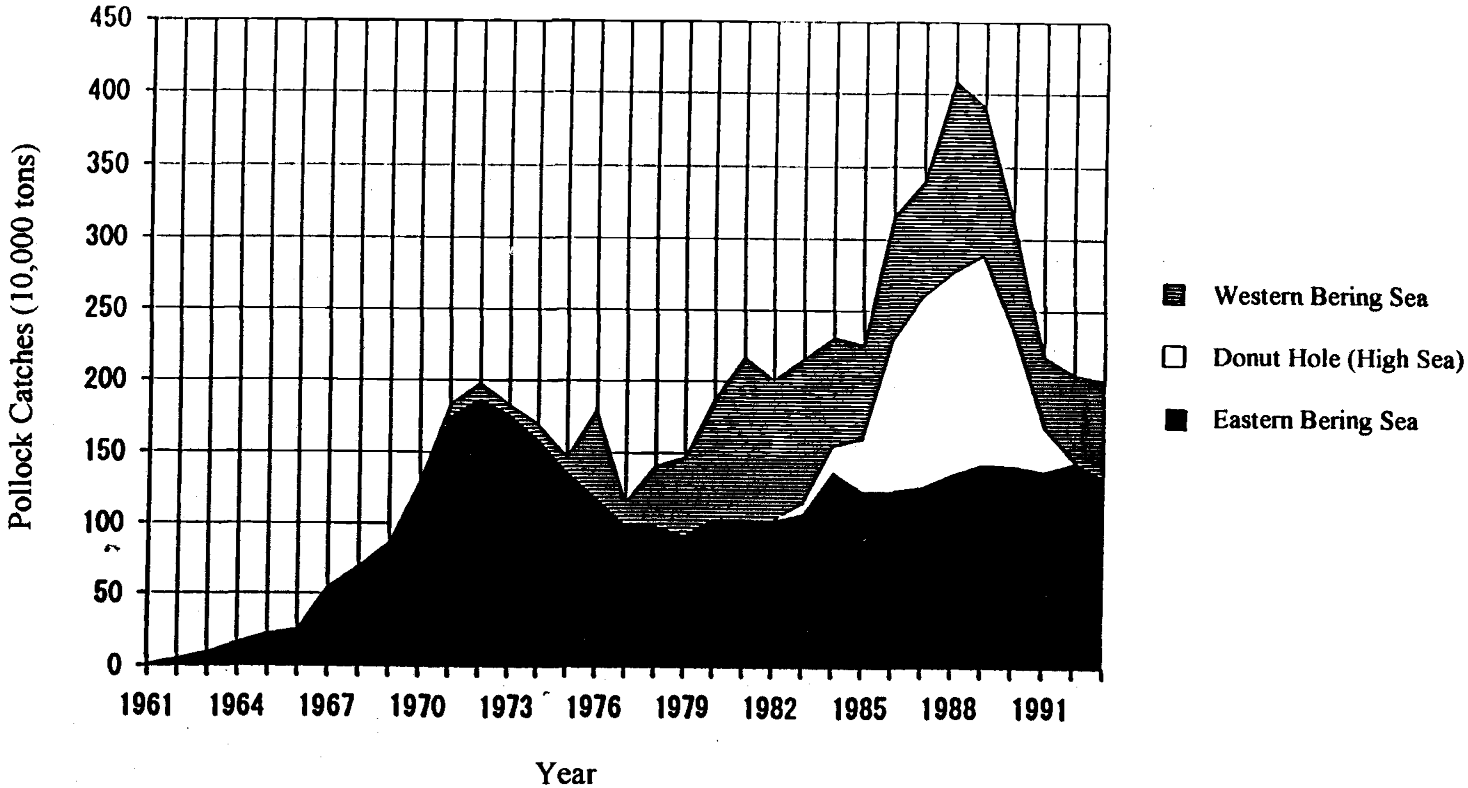

Figure IV. 2 Pollock catches from three areas in the Bering Sea, 1961-1992.
Source: Adapted from Mito (1993).

this Donut Hole became a major international pollock fishing ground for a number of DWF countries.[12]

Table IV.1 shows pollock catches from the Bering Seas and the numbers of operated vessels by countries during 1980 through 1992. Japanese and South Korean trawlers started to harvest pollock in the Donut Hole in 1980. Poland and China entered the Donut Hole in 1985 and Russia, which is a coastal state, joined the high seas fishery group in 1986. The pollock catches in the Donut Hole substantially increased starting in 1986 and reached a peak of approximately 1.45 million metric tons in 1989. The number of operated vessels also gradually increased and reached a peak of 188 vessels in 1988 (103 from Japan, 41 from South Korea, 39 from Poland, 5 from China, and an unknown number from Russia). After 1989, the pollock catches from the Donut Hole dramatically declined and finally, the stock crashed in 1992 so that all countries stopped their pollock fishery in the Donut Hole. The six countries (five DWF countries and the United States) agreed to a voluntarily suspension of the pollock fishery in the Donut Hole during 1993 and 1994. The moratorium continues to the present.

IV. 2. 2 Japanese trawl fisheries in the Bering Sea

Japanese distant-water trawlers in North Pacific waters operate under fishing licenses issued by the Japanese government which restricts the number of trawlers, the size of fishing vessels, and the operating area.. Japanese trawlers consist of four different

[12] Although there are three pollock stocks in the Bering Sea and assessments of Aleutian Basin pollock stock have been limited, it is generally agreed that the Aleutian Basin pollock stock constitutes the most important stock in the high seas Donut Hole (Canfield, 1993). See Figure IV.1.

Table IV.1 Pollock catches (in metric tons) from the Bering High Seas Donut Hole and number of vessels (in parentheses) by country, 1980-1992

Year	Japan		South Korea		Poland		China		Russia		Donut Hole Total	
1980	2,401	(-)	12,059	(-)	0	(0)	0	(0)	0	(0)	14,460	(-)
1981	221	(-)	0	(0)	0	(0)	0	(0)	0	(0)	221	(-)
1982	1,298	(1[†])	2,934	(5)	0	(0)	0	(0)	0	(0)	4,232	(6)
1983	4,096	(2[†])	66,558	(25)	0	(0)	0	(0)	0	(0)	70,654	(27)
1984	100,899	(38[†])	80,317	(26)	0	(0)	0	(0)	0	(0)	181,216	(64)
1985	163,506	(61)	82,444	(26)	115,874	(15)	1,600	(3)	0	(0)	363,424	(105)
1986	705,621	(98)	155,718	(30)	163,249	(15)	3,200	(3)	12,000	(-)	1,039,788	(146)
1987	803,550	(95)	241,870	(32)	230,318	(20)	16,529	(3)	34,000	(-)	1,326,267	(150)
1988	749,982	(103)	268,599	(41)	298,714	(39)	18,419	(5)	61,000	(-)	1,396,714	(188)
1989	654,909	(98)	342,296	(41)	268,570	(39)	31,139	(7)	150,700	(-)	1,447,614	(185)
1990	417,020	(97)	244,271	(41)	223,454	(39)	27,826	(7)	4,800	(-)	917,371	(184)
1991	140,450	(70)	77,959	(31[‡])	54,866	(16[‡])	16,653	(8[‡])	3,471	(-)	293,399	(125)
1992	2,695	(2)	4,018	(-)	0	(0)	3,564	(-)	0	(0)	10,277	(-)

Note: [†] These are generated by using the average catch per vessel (2,680 tons) in 1985.

[‡] These are generated by using each countries' CPUE (tons/hr or tons/day) in 1990 and 1991, which come from Canfield (1993), with the assumption that the each countries' effort per vessel is the same in between 1990 and 1991.

Source: Pollock catches come from the *Annual Fishery Report* (1996) by the Fisheries Agency of Japan.

Number of vessels come from Hayashi (1991) for 1980 to 1989, and from the *Annual Fishery Report* (1996) by the Fisheries Agency of Japan for Japanese data in 1985 to 1992.

groups: *Bosen trawl*, *Hoppo trawl*, *Tenkan trawl*, and *Hokutensen*. The *Bosen trawl* (bosen means "mother-ship") is a trawl fishery including a mother-ship, which is a big vessel carrying processing and freezing equipment. The other three groups are categorized by their operating areas. The *Hoppo trawl* (hoppo means "north") is defined to as a trawl fishery operating in the Pacific Ocean north of 10°N latitude and east of 170°E longitude. The *Tenkan trawl* (tenkan means "conversion") is allowed to operate in the Pacific Ocean north of 50°N latitude ,east of 170°E longitude, and west of 170°W longitude. The *Hokutensen*, which means "the ships that are converted to the northern waters," is a trawler which was converted from working within the Japanese EEZ to the North Pacific Ocean in order to solve a conflict within coastal fisheries in 1961. This trawl fishery is permitted to operate in the North Pacific Ocean north of 48°N latitude ,east of 153°E longitude, and west of 170°W longitude. According to all permitted areas, all four trawl fishery groups can operate a fishery in the Donut Hole.

Figure IV.3 shows Japanese pollock catches from the Bering Sea by four different trawl fishery groups from 1973 to 1994. When the United States and the Soviet Union declared their 200-miles EEZ in March, 1977, total Japanese pollock catches declined by two thirds. The pollock catches by the *Hokutensen* dropped to one sixth of their prior level. Between 1978 and 1983, the Japanese pollock catches were controlled by the quota from the United States and the Soviet Union: around 450,000 metric tons by the *Bosen trawl*; 330,000 metric tons by the *Hoppo trawl*; 5,000 metric tons by the *Tenkan trawl*; and 100,000 metric tons by the *Hokutensen*. The *Boson trawl* was scrapped in 1987 because the quota set by the United States for Japan would be zero in 1988.

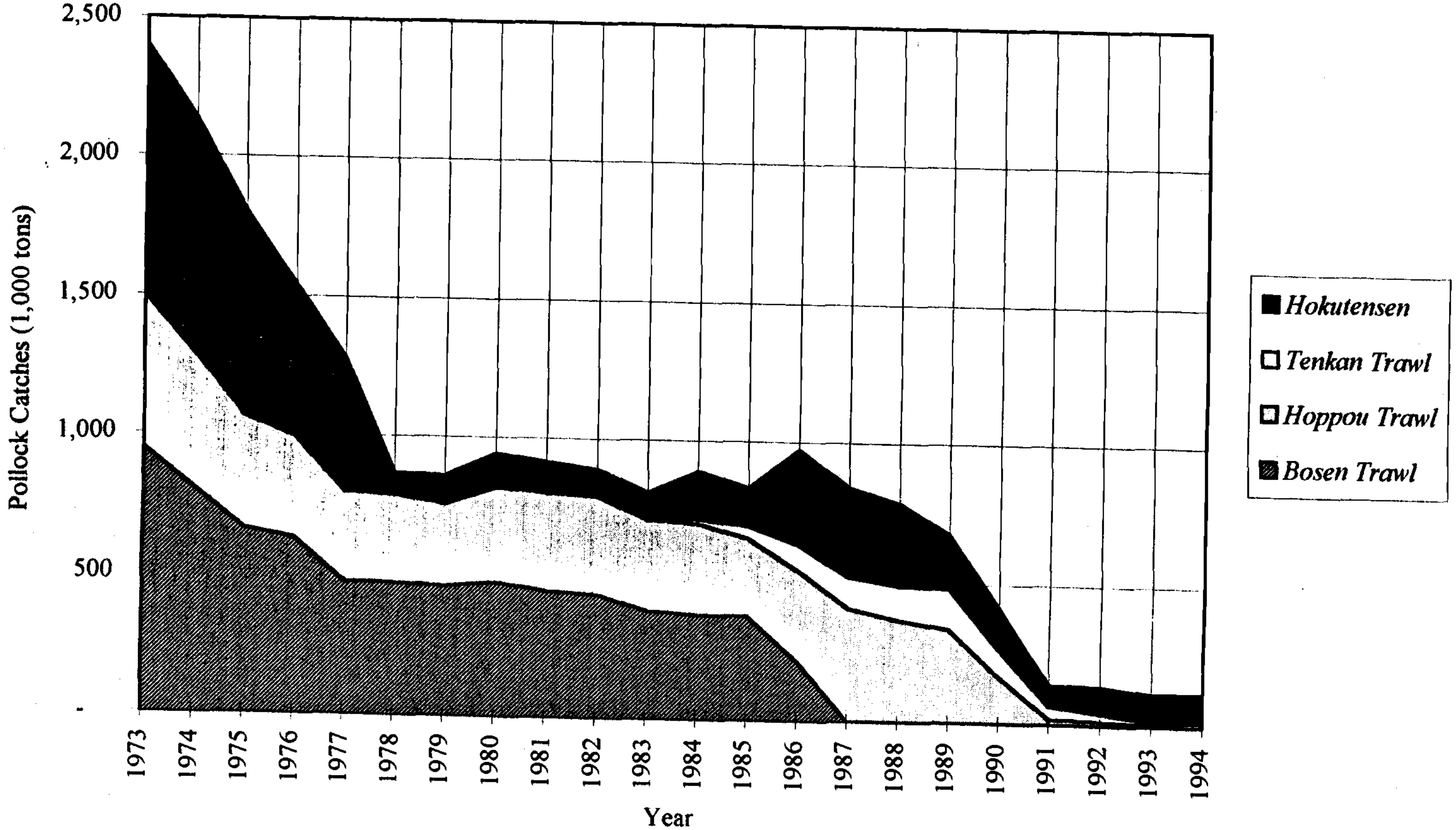

Figure IV. 3 Japanese pollock catches from the entire Bering Sea by four trawl fishery groups, 1973-1994.

In 1984, the pollock catches tripled by the *Tenkan trawl* and doubled by the *Hokutensen*. The increased pollock catches were harvested from the Donut Hole in the Central Bering Sea. The percent of the pollock catches from the Donut Hole to total Japanese pollock catches reached around 70 % in 1986 and 100 % between 1987 and 1991. In October, 1991, the pollock catches suddenly declined substantially (i.e., the crash of the pollock stock), so that all Japanese pollock fishery from the Donut Hole was canceled in June, 1992. Now there is a moratorium on fishing for pollock. After 1992, the pollock catches by the *Hoppo trawl* consistently declined to 15,000 metric tons and the *Tenkan trawl* finally ended in 1994. The *Hokutensen,* however, still harvests pollock at around 100,000 metric tons, which is by a contract for total allowable catch between individual Japanese trawlers and the Russian government.

IV. 3 Dynamic Cournot Harvest of a Common Property Resource

The non-cooperative fisheries in the Donut Hole can be characterized by a dynamic Cournot model. In this section, the dynamic Cournot oligopoly model of Negri (1990), with a state dependent fish growth function, is utilized to solve for a subgame perfect equilibrium on a two-period horizon. The model also derives propositions which are testable predictions about non-cooperative fisheries in the high seas Donut Hole.

IV. 3. 1 The basic model

Suppose there are n harvesters in the Donut Hole denoted as $i = 1, 2, \cdots, n$. Each harvester i chooses the harvest level h_t^i in period t; $t = 1, 2$. The two-period Cournot game begins as follows. In the first period, the harvesters face a fish stock S_t and simultaneously choose harvest level h_t^i and determine their profit. At the beginning of the second period, the harvesters face 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 $t+1$. Since all n harvesters harvest fish from the common fish stock, the total fish harvest in period t, H_t, is the sum of the harvest by all n harvesters:

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

The total fish harvest is non-negative and cannot exceed the fish stock level in the same period ($0 \le H_t \le S_t$).

For simplicity, it is assumed 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 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 dynamics between period 1 and period 2 is

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

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

Further, the unit cost of harvesting fish is assumed to increase with the ratio of harvest to stock. Typically as the stock level falls, it becomes more difficult to harvest fish and unit harvest costs should increase. The cost of harvesting fish, C_t^j, can be written for the n harvesters as

$$C_t^i = \alpha \frac{H_t}{S_t} h_t^i; \quad i = 1, 2, \cdots, n; \; t = 1, 2, \qquad \text{(IV.3)}$$

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

The profit earned by each 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 $0 < P < 2\alpha$.[13] The profits earned in period t by the n harvesters are

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

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

To solve the two-period Cournot model for a subgame perfect equilibrium, backwards induction is used and begins in period 2 (i.e., the last period of the game). When period 2 is reached, the n harvesters face the following profit maximization problem:

$$\max_{h_2^i} \; \pi_2^i(h_2^1, h_2^2, \cdots, h_2^n)$$

[13] To get an interior solution for the subgame perfect equilibrium in this model, the size of P has to be:

$$0 < P < 2\alpha.$$

This is because if P is greater than or equal to 2α, all harvesters will harvest all stock in the first stage and the game will be over.

$$= \max_{h_2^i} \quad h_2^i\left(P - \alpha\frac{H_2}{S_2}\right); \quad i = 1, 2, \cdots, n. \qquad \text{(IV.5)}$$

The first order condition of (IV.5) is set equal to zero to find a typical harvester's best response function.[14] The n identical first-order conditions are summed and solved for the profit maximizing harvest level of all n collective harvesters:

$$H_2^* = \frac{n}{n+1}\frac{P}{\alpha}S_2. \qquad \text{(IV.6)}$$

Dividing the equation by n, the optimal harvest level for each harvester i is

$$h_2^i = \frac{1}{n+1}\frac{P}{\alpha}S_2; \quad i = 1, 2, \cdots, n. \qquad \text{(IV.7)}$$

This equation shows the subgame perfect equilibrium for each harvester in period 2. It is a feedback (subgame perfect) solution and a function of the state of the system in period 2 (i.e., S_2).

Substituting the subgame perfect equilibrium in (IV.7) and the aggregated equilibrium harvest of all harvesters in (IV.6) into the objective function in (IV.5), the one-period optimal value function for each harvester is

$$V_2^{i*}(S_2) = \frac{1}{(n+1)^2}\frac{P^2}{\alpha}S_2; \quad i = 1, 2, \cdots, n. \qquad \text{(IV.8)}$$

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[14] The second-order conditions are satisfied for a maximum in both period 1 and 2. In both cases, the second-order conditions are negative:

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

There is a unique (stable) equilibrium in both period 1 and 2, 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 its own harvest is greater than the absolute value of the second derivative of the firm's profit function with respect to rivals' harvests (Tirole, pp. 226).

Given the second period solutions, the problem for each harvester in period 1 can be derived:

$$\max_{h_1^i} \pi_1^i(h_1^1, h_1^2, \cdots, h_1^n)$$

$$= \max_{h_1^i} h_1^i\left(P - \alpha\frac{H_1}{S_1}\right) + \beta\left[V_2^{i*}(S_2)\right]; \quad i = 1, 2, \cdots, n, \qquad \text{(IV.9)}$$

where β is the discount factor (0 < β <1). Substituting the one-period optimal value function in (IV.8) and the stock growth equation in (IV.2) into equation (IV.9), the optimization problem for the each harvester can be rewritten as

$$\max_{h_1^i} \quad h_1^i\left(P - \alpha\frac{H_1}{S_1}\right) + \frac{1}{(n+1)^2}\frac{\beta P^2}{\alpha}\left[(1+r)S_1 - H_1\right]; \quad i = 1, 2, \cdots, n. \quad \text{(IV.10)}$$

where the size of fish stock in period 1, S_1, is given exogenously. The best response function for each of the n harvesters is found and summed over the n first-order conditions to find the profit maximizing harvest level for the harvesters in period 1. The equilibrium harvest level for the collective harvesters in period 1 is

$$H_1^* = \frac{n}{n+1}\left[1 - \frac{1}{(n+1)^2}\frac{\beta P}{\alpha}\right]\frac{P}{\alpha}S_1, \qquad \text{(IV.11)}$$

Dividing the equation by n gives the optimal harvest level for each harvester in period 1:

$$h_1^{i*} = \frac{1}{n+1}\left[1 - \frac{1}{(n+1)^2}\frac{\beta P}{\alpha}\right]\frac{P}{\alpha}S_1; \quad i = 1, 2, \cdots, n. \qquad \text{(IV.12)}$$

This is the subgame perfect equilibrium for the n harvesters in period 1.

Using the objective function in (IV.10), the two-period optimal value function for each harvester is found by substituting in the subgame perfect equilibrium harvest levels of the collective harvesters in (IV.11) and individual harvester in (IV.12):

$$V_1^{i*} = \frac{1}{(n+1)^2}\left[\left(1-\frac{n^2}{(n+1)^2}\frac{\beta P}{\alpha}\right)\left(1-\frac{1}{(n+1)^2}\frac{\beta P}{\alpha}\right)+\beta(1+r)\right]\frac{P^2}{\alpha}S_1;$$

$$i = 1, 2, \cdots, n. \qquad \text{(IV.13)}$$

Note that the subgame perfect equilibria in (IV.11), (IV.12), and (IV.13) can be solved for an infinite-period horizon (steady state).[15] However, the comparative statics cannot be used for the steady state equilibria because they include a very complex square term. Hence, only a two-period Cournot model is used in this paper.

For the empirical analysis, however, the two-period optimal value cannot be observed; hence, the first-period profit level (π_1^{i*}), which is observable, is used as a proxy of the two-period optimal value (V_1^{i*}). Substituting the equilibrium harvest level for the collective harvesters in (IV.11) and for the individual harvester in (IV.12) into the first term in the objective function in (10), the first-period equilibrium profit level, π_1^{i*}, is

$$\pi_1^{i*} = h_1\left(P-\alpha\frac{H_1}{S_1}\right)$$

$$= \frac{1}{(n+1)^2}\left[1-\frac{1}{(n+1)^2}\frac{\beta P}{\alpha}\right]\left[1+\frac{n}{(n+1)^2}\frac{\beta P}{\alpha}\right]\frac{P^2}{\alpha}S_1. \qquad \text{(IV.14)}$$

The solutions given in (IV.11), (IV.12), and (IV.14) allow one to prove several testable implications for the Bering high seas fisheries. Partial derivatives of the

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[15] The steady state solutions for the collective and individual equilibrium harvest, and individual optimal value are, respectively (the subscript ss denotes the steady-state level):

$$H_{ss}^{*} = \frac{n}{n+1}\Delta\frac{P}{\alpha}S_{ss}\ ;\quad h_{ss}^{i*} = \frac{1}{n+1}\Delta\frac{P}{\alpha}S_{ss}\ ;\quad \text{and}\quad V_{ss}^{i*} = \tilde{d}_{ss}S_{ss} \qquad i = 1, 2, \cdots, n,$$

where $\Delta = 1-\frac{\beta\tilde{d}_{ss}}{P}$ and $\tilde{d}_{ss} = \frac{(n^2+1)P\beta+(n+1)^2\alpha[1-\beta(1+r)]-\sqrt{\omega}}{2n^2\beta^2}$ and

$$\omega = (n^2-1)^2P^2\beta^2+2(n+1)^2(n^2+1)\alpha P\beta[1-\beta(1+r)]+(n+1)^4\alpha^2[1-\beta(1+r)]^2.$$

equilibrium harvest levels for the collective harvesters and for the individual harvester, and the individual equilibrium profit (resource rent) with respect to the number of harvesters n are, respectively:

$$\frac{\partial H_1^*}{\partial n} > 0, \quad \frac{\partial h_1^{i*}}{\partial n} < 0, \quad \frac{\partial \pi_1^{i*}}{\partial n} < 0.$$

These results lead to the following proposition (see the Appendix A for proofs of the propositions).

Proposition IV.1: *An increase in the number of harvesters in an high seas fishery increases the collective equilibrium harvest level by all harvesters, but reduces both the equilibrium harvest and profit (resource rent) level for the individual harvester.*

Entry affects fishing cost through both dynamic stock and static crowding externalities. The dynamic stock externality decreases user cost by reducing stock size in the second period, conversely, the static crowding externality increases the harvesting cost in each period. In total, the net harvesting costs increase, which reduces the harvest levels of the individual harvester. Entry and the corresponding externalities, therefore, reduce the resource rent for all harvesters by reducing profits in both periods.

Comparative statics show other implications for the fishery in the Donut Hole. The partial derivatives of the equilibrium harvest level for the collective harvesters and the individual harvester, and the individual equilibrium profit with respect to parameter P, α, β and S are, respectively (see the Appendix B for derivations):

$$\frac{\partial H_1^*}{\partial P} > 0, \quad \frac{\partial h_1^{i*}}{\partial P} > 0, \quad \frac{\partial \pi_1^{i*}}{\partial P} > 0,$$

$$\frac{\partial H_1^*}{\partial \alpha} < 0, \quad \frac{\partial h_1^{i*}}{\partial \alpha} < 0, \quad \frac{\partial \pi_1^{i*}}{\partial \alpha} < 0,$$

$$\frac{\partial H_1^*}{\partial \beta} < 0, \quad \frac{\partial h_1^{i*}}{\partial \beta} < 0, \quad \frac{\partial \pi_1^{i*}}{\partial \beta} > 0,$$

$$\frac{\partial H_1^*}{\partial S} > 0, \quad \frac{\partial h_1^{i*}}{\partial S} > 0, \quad \frac{\partial \pi_1^{i*}}{\partial S} > 0.$$

The discount factor can be written as $\beta = 1/(1+\delta)$, where δ is the periodic discount rate. Hence, the partial derivatives of the three equilibrium levels with respect to the discount rate is

$$\frac{\partial H_1^*}{\partial \delta} > 0, \quad \frac{\partial h_1^{i*}}{\partial \delta} > 0, \quad \frac{\partial \pi_1^{i*}}{\partial \delta} < 0.$$

IV. 3. 2 The extended model for variable number of harvesters

Up to now, the number of harvesters (n) is assumed to be fixed in both period 1 and 2. However, the expectation of the next period n might affect the three equilibrium levels in the current period. So the extension is that the number of harvesters (n) is allowed to change between the two periods in the basic model (the other parameters remain fixed between the two periods). Let n_1 and n_2 denote the number of harvesters in period 1 and 2, respectively. If the number of harvesters (n) is allowed to change between the two periods; the three equilibrium levels in equations (IV.11), (IV.12), and (IV.14) can be rewritten, respectively as:

$$H_1^* = \frac{n_1}{n_1+1}\left[1 - \frac{1}{(n_2+1)^2}\frac{\beta P}{\alpha}\right]\frac{P}{\alpha}S_1; \qquad \text{(IV.15)}$$

$$h_1^{i*} = \frac{1}{n_1+1}\left[1-\frac{1}{(n_2+1)^2}\frac{\beta P}{\alpha}\right]\frac{P}{\alpha}S_1\text{; and} \qquad \text{(IV.16)}$$

$$\pi_1^{i*} = \frac{1}{(n_1+1)^2}\left[(n_1+1)\left(1-\frac{1}{(n_2+1)^2}\frac{\beta P}{\alpha}\right)-n_1\left(1-\frac{1}{(n_2+1)^2}\frac{\beta P}{\alpha}\right)^2\right]\frac{P^2}{\alpha}S_1. \qquad \text{(IV.17)}$$

Using these three alternative equilibrium solutions, the partial derivatives of the equilibrium harvest levels for the collective harvesters and for the individual harvester, and the equilibrium profit level for the individual harvester with respect to n_1 are, respectively:

$$\frac{\partial H_1^*}{\partial n_1} > 0, \quad \frac{\partial h_1^{i*}}{\partial n_1} < 0, \quad \frac{\partial \pi_1^{i*}}{\partial n_1} < 0.$$

Also, the partial derivatives of the three equilibrium levels with respect to n_2 are, respectively:

$$\frac{\partial H_1^*}{\partial n_2} > 0, \quad \frac{\partial h_1^{i*}}{\partial n_2} > 0, \quad \frac{\partial \pi_1^{i*}}{\partial n_2} > 0.$$

These results can be summarized in the following proposition.

Proposition IV.2: *If the number of harvesters changes between the current and next period, an increase in the number of harvesters in the current period increases the collective equilibrium harvest level by all harvesters, but reduces both the equilibrium harvest and profit (resource rent) level for the individual harvester. On the other hand, an increase in the number of harvesters in the next period, which is the future expectation of the number of harvesters, increases all three equilibrium levels.*

While the effects of the current entry on the equilibrium levels are the same as the ones by the original case in proposition IV.1, the effects of the expected future entry are different from the original results. The individual harvesters increase both the equilibrium harvest and profit level if they expect the future entry will increase, given fixed current harvesters. There is no dynamic stock externality since the current number of harvesters does not change, but, the static crowding externality increases the harvesting cost only in the second period, which decreases user cost. As a result, the reduced user cost, which implies the reservation of the stock is less valuable, causes a higher equilibrium harvest level. Further, the increase in the harvest level results in a greater first-period profit without static crowding externality in the first period.

IV. 4 The Empirical Model

The econometric equations to be estimated are based on three equilibrium equations in the previous section: the collective equilibrium harvest by all harvesters (H) in equation (IV.11); the individual equilibrium harvest (h) in equation (IV.12); and the first-period equilibrium profit for each harvester (π) in equation (IV.14). These three equilibrium levels (dependent variables) are identified as a function of five independent variables: the number of harvesters (fishing vessels) (n); the price of the pollock harvested (P); the cost parameter (α); the discount rate (δ); and the fish stock (S).

For empirical analysis, the cost parameter (α) is provided by average (total) cost (i.e., unit cost of harvest), which is the total cost divided by the total harvest (hereafter, the cost parameter (α) is called average cost). The average total cost includes average fixed cost, for which the depreciation of vessel, building, and equipment is used. Note that during years that pollock was harvested from the Donut Hole (1980 through 1991), the technology of the fishery did not change much (e.g., only 6 of the *Hokutensen* 97 vessels were improved for energy saving equipment). Also, catch per unit effort (CPUE) is used as a proxy of pollock stock level (*S*) in the Donut Hole, because there are no reliable data for the pollock stock in the Donut Hole. This is based on the assumption (i.e., the catch-per-unit-effort hypothesis or the Schaefer hypothesis) that CPUE is proportional to the current stock size (Clark, 1990).[16]

There might be, however, two problems with these explanatory variables. First, it is merely an hypothesis that the CPUE is a linear function of the fish stock. If it is not a linear but rather a nonlinear function, then the CPUE hypothesis results in a specification error due to omitting a relevant explanatory variables (e.g., the omission of the square term of the fish stock). Hence, the OLS estimator of the coefficients will be biased and inconsistent, and the OLS estimator of the variance of the coefficients will contain an upward bias. Second, inclusion of both the average cost and the CPUE causes a multicollinearity problem because the CPUE is likely to be highly correlated with the unit variable cost. One of the remedies for this problem is to drop either one of explanatory variables from the model.

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[16] The Schaefer hypothesis is expressed as $H = qES$, where H, q, E, and S denotes the catch rate, the catchability coefficient, fishing effort, and the fish stock, respectively (Schaefer, 1954). Hence, the CPUE is shown as:

$$\frac{H}{E} = qS,$$

which is a linear function of the fish stock level.

In general form, the above three equilibrium levels at time t can be written as a function of n, P, α, δ, and S:

$$H_t = H(n_t, P_t, \alpha_t, \delta_t, S_t), \tag{IV.18a}$$

$$h_t = h(n_t, P_t, \alpha_t, \delta_t, S_t), \text{ and} \tag{IV.18b}$$

$$\pi_t = \pi(n_t, P_t, \alpha_t, \delta_t, S_t). \tag{IV.18c}$$

If proposition IV.1 in Section IV. 3 is correct, then:

i) $H_n(\cdot) > 0$,

ii) $h_n(\cdot) < 0$, and

iii) $\pi_n(\cdot) < 0$,

where subscripts indicate partial derivatives with respect to n. On the other hand, if proposition IV.2 in Section IV. 3 is true, then:

iv) $H_{n_1}(\cdot) > 0$, $H_{n_2}(\cdot) > 0$;

v) $h_{n_1}(\cdot) < 0$, $h_{n_2}(\cdot) > 0$; and

vi) $\pi_{n_1}(\cdot) < 0$, $\pi_{n_2}(\cdot) > 0$;

where subscripts indicate partial derivatives with respect to n_1 and n_2 (i.e., n is divided into two terms: n_1 and n_2).

Figure IV.4 shows the relationship between three equilibrium levels (H_t, h_t, and π_t) and the number of harvesters (n_t) for a given level of other right-hand-side explanatory variables: P = 1, α = 1, β = 0.9, r = 0.5, and S = 1. These relationships can be

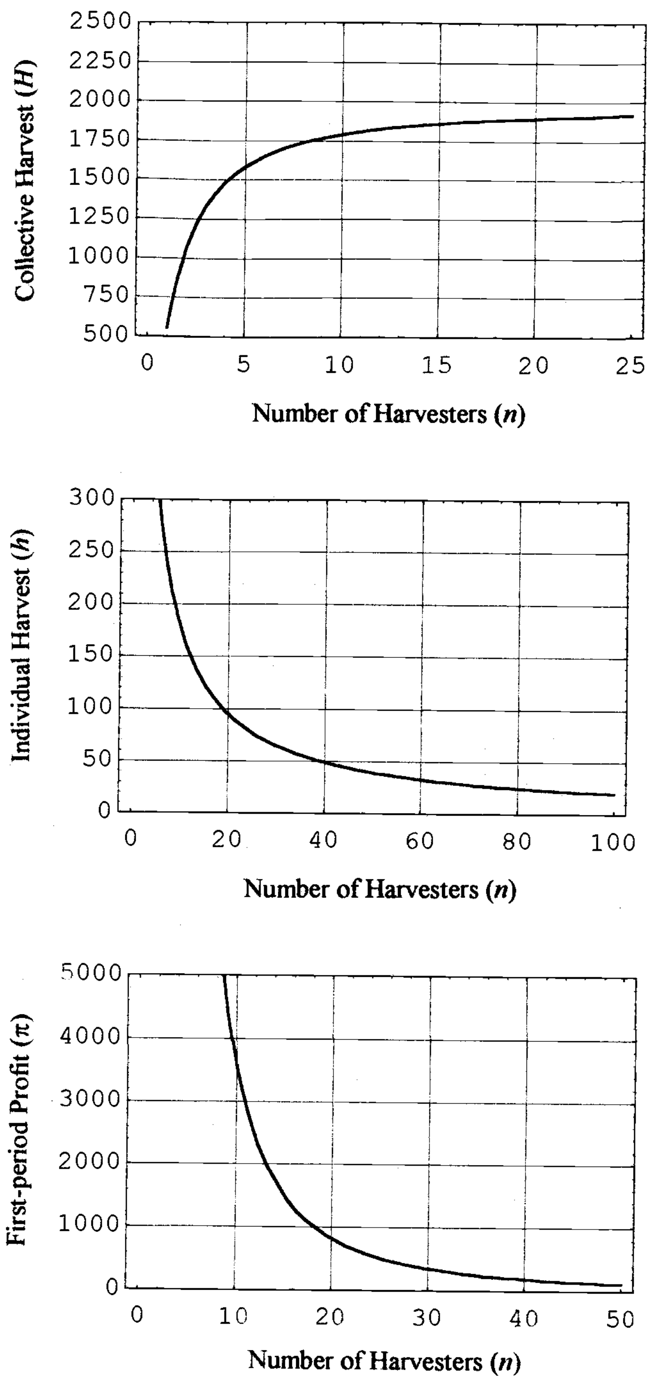

Figure IV. 4 Relationship between number of harvesters and three equilibrium levels.

approximated by using an exponential function[17], so that the following exponential function is used as an approximation for the general model:

$$H_t = \lambda_H \cdot n_t^{\beta_1} \cdot u_{H,t}, \tag{IV.19a}$$

$$h_t = \lambda_h \cdot n_t^{\gamma_1} \cdot u_{h,t}, \text{ and} \tag{IV.19b}$$

$$\pi_t = \lambda_\pi \cdot n_t^{\theta_1} \cdot u_{\pi,t}, \tag{IV.19c}$$

where u's are disturbance terms at time t, which is added because of random errors in optimization, and $\lambda_H = e^{\beta_0} P_t^{\beta_2} \alpha_t^{\beta_3} \delta_t^{\beta_4} S_t^{\beta_5}$, $\lambda_h = e^{\gamma_0} P_t^{\gamma_2} \alpha_t^{\gamma_3} \delta_t^{\gamma_4} S_t^{\gamma_5}$, and $\lambda_\pi = e^{\theta_0} P_t^{\theta_2} \alpha_t^{\theta_3} \delta_t^{\theta_4} S_t^{\theta_5}$. It is assumed that errors (u's) enter multiplicatively because some common unmeasurable or omitted variables will create proportionately large errors in large harvest or profit years. Taking natural logs of both sides of equations (IV.19a), (IV.19b), and (IV.19c) gives a log-linear specification:

$$\ln H_t = \beta_0 + \beta_1 \ln n_t + \beta_2 \ln P_t + \beta_3 \ln \alpha_t + \beta_4 \ln \delta_t + \beta_5 \ln S_t + \varepsilon_{H,t}, \tag{IV.20a}$$

$$\ln h_t = \gamma_0 + \gamma_1 \ln n_t + \gamma_2 \ln P_t + \gamma_3 \ln \alpha_t + \gamma_4 \ln \delta_t + \gamma_5 \ln S_t + \varepsilon_{h,t}, \text{ and} \tag{IV.20b}$$

$$\ln \pi_t = \theta_0 + \theta_1 \ln n_t + \theta_2 \ln P_t + \theta_3 \ln \alpha_t + \theta_4 \ln \delta_t + \theta_5 \ln S_t + \varepsilon_{\pi,t}, \tag{IV.20c}$$

where $\varepsilon = \ln u$, and β, γ, and θ are coefficients to be estimated. The log-linear equation in (IV.20c), however, cannot be used for estimation in this paper because the data on individual harvester's profit include some negative values. Therefore, instead of using log-linear form, a semilog specification is used for the first-period profit equation in (IV.20c):

$$\pi_t = \theta_0 + \theta_1 \ln n_t + \theta_2 \ln P_t + \theta_3 \ln \alpha_t + \theta_4 \ln \delta_t + \theta_5 \ln S_t + \varepsilon_{\pi,t}, \tag{IV.20d}$$

[17] This nonlinear shape is created by the cost function in equation (IV.3).

where the original exponential equation for the semilog specification is: $e^{\pi_t} = \lambda_\pi \cdot n_t^{\theta_1} \cdot u_{\pi,t}$.

For the test of proposition IV.2, another term for the expected number of future harvesters, n^e, is added in the model: $\beta_6 \ln n_t^e$ (IV.20a), $\gamma_6 \ln n_t^e$ (IV.20b), and $\theta_6 \ln n_t^e$ (IV.20d). For this term, it is assumed that the harvesters' expectation in the next period is a trend of the number of harvesters between the previous and current period. The expected number of future harvesters (n^e) is calculated by the following formula: n^e = $n_1 \cdot (n_1 - n_0)/n_0 + n_1$, where n_1 is the current number and n_0 is the previous number of harvesters.

The disturbances at a given time in three equations are likely to reflect some common unmeasurable or omitted factors; hence, they could be correlated (i.e., contemporaneous correlation). When this is the case, it may be more efficient to estimate all equations (IV.20a, IV.20b, and IV.20d) jointly rather than to estimate by using equation-by-equation ordinary least squares (OLS). In these three equations, however, the right-hand-side explanatory variables in these three equations are identical so that the parameter estimates by SUR estimation are identical with that by equation-by equation OLS estimation (there is no efficiency gain). In this paper, therefore, equation-by-equation OLS is used for the estimation.

In this econometrics model, there might be a simultaneity problem. The price of pollock (P) and the average cost (α) might be endogenous. The price of pollock in the Japanese market is thought to be determined by the total harvest level by all the *Hokutensen*, which is positively related to the collective harvest (H) from the Donut Hole (i.e., the total Japanese pollock catches are around 53.1% of total catches by six DWF countries between 1982 and 1991). Also, the average cost may depend on the collective harvest (*H*) level. If a simultaneity problem exists, the OLS estimator is biased and inconsistent, so that two stage least squares (2SLS) or three stage least squares (3SLS) estimation should be used, if any, with instrumental variables. When samples are extremely small, however, the distributions for 2SLS and 3SLS estimators are not known to be normal and the mean of the 2SLS estimator may not exist. In addition, in small samples, the OLS estimator (despite their inconsistency) has a lower variance than the 2SLS estimator (Judge, *et al.*, 1988, pp. 655). Therefore, the 2SLS and 3SLS estimation may not be appropriate methods to use with these data.

A dummy variable (*D*), taking the value zero in 1982 through 1985, and value one afterwards, is included in all three equilibrium equations (IV.20a, IV.20b, and IV.20d). This is because, in 1982 through 1985, the *Hokutensen* trawlers harvested pollock not only from the Donut Hole but from the Russian and the U.S. EEZ on a quota, while in 1986 through 1991, they primarily harvested pollock from the Donut Hole.[18] Although it may be better to drop these four observations, including them with the dummy variable allows more degrees of freedom, which is very important in this very small sample.

[18] There is one concern with using this dummy variable. The *Hokutensen* trawlers harvested pollock from the Donut Hole almost 100% between 1986 and 1991 and around 1% in 1982 and 1983, which correlate with the 1 and 0 dummy variables. However, the percentage of the pollock harvest from the Donut Hole out of the whole Bering Sea's yearly harvest were 20% and 36% in 1984 and 1985, respectively. An alternative way to take care of this situation is to use the quota from the U.S. as a explanatory variable instead of the dummy variable, since the percentage change in the Donut Hole was caused by the decrease in the quota from the U.S.. Unfortunately, the result of using the quota variable is almost identical with the one using the dummy variable and some estimates change to unexpected signs. So the simple dummy variable is used in this study.

The theoretical analysis in the previous section tells us *a priori* the signs of the parameters: $\beta_1 > 0$, $\beta_2 > 0$, $\beta_3 < 0$, $\beta_4 > 0$, $\beta_5 > 0$, and $\beta_6 > 0$ for the collective harvest equation (H); $\gamma_1 < 0$, $\gamma_2 > 0$, $\gamma_3 < 0$, $\gamma_4 > 0$, $\gamma_5 > 0$, and $\gamma_6 > 0$ for the individual harvest equation (h); and $\theta_1 < 0$, $\theta_2 > 0$, $\theta_3 < 0$, $\theta_4 < 0$, $\theta_5 > 0$, and $\theta_6 > 0$ for the first-period profit equation (π). For the purpose of this paper, the main parameters of interest are β_1, β_6, γ_1, γ_6, θ_1, and θ_6.

IV. 5 Data

The empirical analysis uses data from the *Hokutensen* Japanese trawl fishery, which harvested pollock stock from the Donut Hole in the Bering Sea during a 10-year period from 1982 to 1991.[19] The Japanese government publishes annual economic data for only the *Hokutensen* as a representative of the distant-water trawling fishery in the *Investigation Report of Fishery Economics* by the Ministry of Agriculture, Forestry and Fishery (Japan).[20] These data are not for individual vessel levels but an average of

[19] As Table IV.1 showed, pollock stocks were harvested from the Donut Hole during a 13-year period from 1980 to 1992. However, the data for the first two years (1980 and 1981) and the last year (1992) are excluded from the analysis. The former is because the Japanese pollock catch (221 tons) in 1981 was much less than the average catch per vessel (2,680 tons) by Japan in 1985. The latter because the Japanese pollock catch in 1992 was canceled in June.

[20] The English titles for the Japanese publications in this section are translated from Japanese by the author.

randomly selected vessels (i.e., group mean data[21]); hence, the observation number is only ten (time series). In each year, the number of randomly selected samples (harvesters) are different. The average number of the sample vessels is 8.2 between 1982 and 1991, while the average number of the total *Hokutensen* vessels is 66.2. The data are collected by questionnaires and direct interviews from randomly selected harvesters. The data include average vessel weight, number of working days and workers, total revenue from the fishery, variable costs (including labor, fuel, material, repair cost, fees, and other cost), fixed capital cost, capital depreciation and wages (for one person a day). Data for the other Japanese trawl groups described in Section IV.2 are not available.

For the data on dependent variables, the collective pollock harvest (H) from the Donut Hole by five countries are obtained from the *Annual Fishery Report* in 1996 by the Fisheries Agency of Japan (see Table IV.1). Data for the individual harvest of pollock (h) are calculated by dividing the *Hokutensen* pollock catches by the number of the *Hokutensen* harvesters (vessels). These data come from the *Annual Statistical Report of Fishery and Aquaculture Production* by the Ministry of Agriculture, Forestry and Fishery (Japan). The sizes of the *Hokutensen* vessels are all between 200 to 500 tons with an average of 314.7 tons between 1982 and 1991. As a proxy of two-period value (V), the individual harvester's profit (π) is calculated by subtracting total cost (variable cost plus

[21] There are two effects when the group mean date is used. First, the parameter estimates are less efficient because of the loss of information. Second, the fit of the regression sometime improves greatly. See Green (1990), pp.289-293.

capital depreciation) from total revenue [22], which comes from the *Investigation Report of Fishery Economics* by the Ministry of Agriculture, Forestry and Fishery (Japan).

For the data on explanatory variables, the number of harvesters (n) in the Donut Hole is obtained from Hayashi (1991) for 1980-1989, and from the *Annual Fishery Report* in 1996 by the Fisheries Agency of Japan for Japanese data in 1985 to 1992 (see Table IV.1). There are, however, some missing data in the article by Hayashi. The missing data for the number of Japanese harvesters in 1982, 1983, and 1984 are generated by using the average catch per vessel (2,680 tons) in 1985. The missing data for South Korea, Poland, and China in 1991 are generated by using each countries' CPUE (tons / hr or tons / day) in 1990 and 1991, which come from Canfield (1993) (i.e., it is assumed that fishing hours or days per vessel are the same for 1990 and 1991). The expected number of future harvesters (n^e) is generated by using the previous and the current number of harvesters as described in the previous section.

In addition, data for the price of the harvested pollock (P) are obtained from the *Annual Statistical Report of Fishery Product Market* by the Ministry of Agriculture, Forestry and Fishery (Japan). The discount rate (δ) used is the 10 year government bond yield to subscribers, which is obtained from the *Economic Statistics Annual* by the Research and Statistics Department, Bank of Japan. The other explanatory variables, cost parameter (α) and fish stock (S), are substituted by using (total) average cost and catch per unit effort, respectively. The former is derived by dividing total cost (variable cost

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[22] The total revenue includes the earnings for not only pollock but also the other groundfish: cod, flounder, rockfish, lockington, and squid. However, the percent of pollock catch to total fish catch was 93.6% between 1984 and 1991.

plus capital depreciation) by the individual harvest level (yen / tons) and the latter is calculated by dividing the total *Hokutensen* pollock catches by vessel-days, which is measured by the number of the *Hokutensen* vessels multiplied by the number of working days (tons / vessels-days).

For the instrumental variables, the price of surimi (processed pollock) comes from the *Annual Statistical Report of Fishery Product Market* by the Ministry of Agriculture, Forestry and Fishery (Japan). The price of heavy fuel oil A comes from the *Price Indexes Annual* by the Research and Statistics Department, Bank of Japan. Finally, national income is obtained from the *Annual Report on National Accounts* by the Economic Planning Agency (Japan).

IV. 6 Empirical Results

Table IV.2 presents the estimation results of the regression equations based on (IV.20a), (IV.20b), and (IV.20d). Three equilibrium equations (H, h, and π) are estimated by equation-by-equation ordinary least squares (OLS). Estimates of the standard errors are shown in parentheses below the estimates of the coefficients. For t-test of each parameter estimate, a one-tailed test is used because the theoretical model in Section IV. 3 provides all signs of the parameter estimates. One, two, and three stars indicate that parameter estimates are statistically significant at the 10%, 5%, and 1% confidence level, respectively.

Table IV. 2
Parameter estimates by equation-by-equation ordinary least squares (OLS) estimation

Variables	Equations (OLS)		
	Log-linear		Semilog
	Collective harvest (H)	Individual harvest (h)	First-period profit (π)
Constant	34.536** (13.30)	19.641*** (4.507)	-10.271 (33.44)
Number of harvesters (n)	1.8879*** (0.2888)	-0.096699 (0.09785)	-1.3340* (0.7259)
Price of pollock (P)	-0.26119† (0.3534)	0.59440*** (0.1197)	0.93937 (0.8882)
Average cost (α)	-4.0002** (1.536)	-1.4435** (0.5202)	0.81062† (3.859)
Discount rate (δ)	-2.4534† (1.999)	-3.0249***† (0.6771)	0.17272† (5.023)
Fish Stock (S)	-3.8164*† (1.688)	-0.34639† (0.5719)	2.6605 (4.243)
Dummy (D)	-0.42640 (0.4135)	-0.20087 (0.1401)	-0.26811 (1.039)
R^2	0.9936	0.9950	0.7966
DW	3.0435	3.4593	3.0847

Standard errors are in parentheses.
* Statistically significant at 10 % significance level (one-tailed test with 3 d.f.).
** Statistically significant at 5 % significance level (one-tailed test with 3 d.f.).
*** Statistically significant at 1 % significance level (one-tailed test with 3 d.f.).
† Unexpected sign.

Overall, around half of the parameter estimates (53.3%) exhibit the expected signs. The estimated coefficients for the number of harvesters (n) have the expected signs for all three equations and are statistically significant at the 1% and 10% confidence level for equations (H) and (π), respectively, but not statistically significant for equation (h). The other variables, having expected signs, that are statistically significant are the price of pollock (P) in equations (h) and the average cost (α) in equations (H) and (h). The estimated price elasticity of supply is 0.5944 (i.e., inelastic), which is statistically significant at the 1% confidence level.

The R^2s in each equation are high: 0.9936 for equation (H), 0.9950 for equation (h), and 0.7966 for equation (π). The Durbin-Watson (DW) statistics for each equation are 3.0435 for equation (H), 3.4593 for equation (h), and 3.0847 for equation (π). Though the critical values of the DW statistic are not available due to the small sample size, the computer program (SHAZAM) computes DW P-values: 0.5025 for equation (H), 0.7745 for equation (h), and 0.13563 for equation (π). These values indicate that the null hypothesis, no negative autocorrelation, cannot be rejected at less than the 10% significance level. In this thesis, however, negative autocorrelation cannot be corrected at all because of the small observation numbers.

In the previous OLS estimation, it was assumed that all explanatory variables were exogenous. However, there might be a simultaneity problem, because the two explanatory variables, the price of pollock (P) and the average cost (α), might be endogenous as discussed in Section IV. 4. To correct for the simultaneity problem, a three stage least squares (3SLS) estimation is used for three equations (H, h, and π).[23]

Table IV.3 presents the parameter estimates by 3SLS estimations. In this estimation, there are five endogenous variables (H, h, π, P, and α) and eight exogenous variables (n, δ, S, D and the four instrumental variables: the surimi price, oil input price, Japanese national income, and time as an index of the level of technology). The system generalized R^2 is very high (1.0000).[24] The results of each parameter estimate are very similar to the ones using the OLS estimation. The estimated coefficients on the number of harvesters (n) are still statistically significant in equations (H) and (π). The sign for the all estimated coefficients does not change at all. The estimated price elasticity of supply (0.58755) does not change much and is still statistically significant at the 1% confidence level.

There is also the problem of multicollinearity in the econometric model because the CPUE, a proxy of the fish stock level (S), is likely to be highly correlated with the average cost, a proxy of the cost parameter (α). Indeed, the correlation between these two variables is extremely high (-0.9832). To examine this problem, the original

[23] One of the other ways to correct for the simultaneity problem is to use the lagged price of pollock (the price in the previous year) which is an exogenous variable. However, the correlation between the lagged price of pollock and the individual harvest level (dependent variable) is extremely small (-0.2451). Hence, the lagged price is not used in this study.

[24] The generalized R^2, $\tilde{R}^2$, is defined as the proportion of the generalized variance in the cross-product matrix of dependent variable Y by variation in the explanatory variables in the system of equations, and is computed as:

$$\tilde{R}^2 = 1 - \frac{|E'E|}{|y'y|},$$

where E is the residual cross-products matrix and $y = Y - \bar{Y}$ (Berndt, 1991, pp. 468).

Table IV. 3
Parameter estimates by three stage least squares (3SLS) estimation

Variables	Equations (3SLS)		
	Log-linear		Semilog
	Collective harvest (*H*)	Individual harvest (*h*)	First-period profit (π)
Constant	34.999**	18.933**	-10.507
	(13.53)	(4.611)	(34.01)
Number of harvesters (*n*)	1.8957***	-0.10856	-1.3380*
	(0.29187)	(0.09943)	(0.7333)
Price of pollock (*P*)	-0.25671 †	0.58755***	0.93708
	(0.3543)	(0.1207)	(0.8902)
Average cost (α)	-4.0610**	-1.3506**	0.84166 †
	(1.570)	(0.5348)	(3.944)
Discount rate (δ)	-2.4719 †	-2.9965** †	0.18220 †
	(2.002)	(0.6819)	(5.029)
Fish Stock (*S*)	-3.8782* †	-0.25187 †	2.6921
	(1.721)	(0.5862)	(4.323)
Dummy (*D*)	-0.42471	-0.20346	-0.26898
	(0.4137)	(0.1409)	(1.039)
R^2	0.9935	0.9949	0.7966
DW	3.0579	3.4092	3.0817

Standard errors are in parentheses.
Systems generalized R^2: 1.0000.
* Statistically significant at 10 % significance level (one-tailed test with 3 d.f.).
** Statistically significant at 5 % significance level (one-tailed test with 3 d.f.).
*** Statistically significant at 1 % significance level (one-tailed test with 3 d.f.).
† Unexpected sign.

econometric model based on three equations (IV.20a, IV.20b, and IV.20d) is estimated by dropping the fish stock (S) term. One of the reasons for using this alternative specification is that the fish stock level in the Donut Hole might not be known by the *Hokutensen* trawlers.

Table IV.4 shows the estimation results by equation-by-equation OLS with the alternative specification of dropping the fish stock (S) term. There are now three estimated parameter with unexpected sign: the price of pollock (P) in equation (H) and the discount rate (δ) in equations (H) and (h). The estimated coefficients of the number of harvesters (n) have the expected signs in all three equations and are statistically significant at the 1% confidence level for equation (H), and at the 5% confidence level for equations (h) and (π). All three parameter estimates for average cost (α) now have the expected sign and are statistically significant. R^2s by equation-by-equation OLS for all equations are not changed much. A computer program provides DW P-values: 0.04453 for equation (H),0.7024 for equation (h), and 0.4680 for equation (π). While the first value shows the rejection of the null hypothesis, no negative autocorrelation, at less than the 5% significance level, the last two values still indicate that the null hypothesis cannot be rejected at less than the 10% significance level.

For the alternative specification, three equations can be estimated by the 3SLS estimation and their results are reported in Table IV.5. The systems generalized R^2 is still very high (0.9998). The results for all three equations are almost equivalent to the ones in Table IV.4. Three parameter estimate have an unexpected sign. The estimated

Table IV. 4
Parameter estimates by equation-by-equation ordinary least squares (OLS) estimation on an alternative specification (dropping fish stock term)

Variables	Equations (OLS)		
	Log-linear		Semilog
	Collective harvest (H)	Individual harvest (h)	First-period profit (π)
Constant	5.4115 (4.720)	16.998*** (1.030)	10.033* (7.673)
Number of harvesters (n)	1.3469*** (0.2303)	-0.14580** (0.05026)	-0.95685** (0.3743)
Price of pollock (P)	-0.13920 † (0.4973)	0.60547*** (0.1085)	0.85433 (0.8084)
Average cost (α)	-0.63981 (0.5477)	-1.1385*** (0.1195)	-1.5320* (0.8903)
Discount rate (δ)	-0.79818 † (2.648)	-2.8748*** † (0.5780)	-0.98115 (4.305)
Fish Stock (S)	- -	- -	- -
Dummy (D)	-0.33883 (0.5862)	-0.19292 (0.1279)	-0.32916 (0.9529)
R^2	0.9826	0.9943	0.7700
DW	2.4214	3.2671	3.1019

Standard errors are in parentheses.
* Statistically significant at 10 % significance level (one-tailed test with 4 d.f.).
** Statistically significant at 5 % significance level (one-tailed test with 4 d.f.).
*** Statistically significant at 1 % significance level (one-tailed test with 4 d.f.).
† Unexpected sign.

Table IV. 5
Parameter estimates by three stage least squares (3SLS) estimation on an alternative specification (dropping fish stock term)

Variables	Equations (3SLS)		
	Log-linear		Semilog
	Collective harvest (H)	Individual harvest (h)	First-period profit (π)
Constant	5.3310 (4.755)	16.954*** (1.083)	10.109 (7.696)
Number of harvesters (n)	1.3442*** (0.2320)	-0.14667** (0.05284)	-0.95414** (0.3756)
Price of pollock (P)	-0.15301† (0.5030)	0.59122*** (0.1145)	0.86641 (0.8141)
Average cost (α)	-0.74222 (0.5962)	-1.1975*** (0.1358)	-1.4355 (0.9651)
Discount rate (δ)	-0.42626† (2.774)	-2.6479**† (0.6318)	-1.3298 (4.491)
Fish Stock (S)	- -	- -	- -
Dummy (D)	-0.30909 (0.5943)	-0.17691* (0.1353)	-0.35734 (0.9620)
R^2	0.9824	0.9938	0.7690
DW	2.4643	3.3578	3.0463

Standard errors are in parentheses.
Systems generalized R^2: 0.9998.
* Statistically significant at 10 % significance level (one-tailed test with 4 d.f.).
** Statistically significant at 5 % significance level (one-tailed test with 4 d.f.).
*** Statistically significant at 1 % significance level (one-tailed test with 4 d.f.).
† Unexpected sign.

coefficients on the number of harvesters (*n*) still have the expected signs for all three equations and are statistically significant in all three equations.

Finally, the effect of future expectation of the harvesters is examined by adding the expected harvesters term in the alternative model, without a fish stock term. Table IV.6 shows the estimation results by equation-by-equation OLS. Equation-by-equation R^2s by OLS are still high: 0.9881 for equations (*H*), 0.9987 for equation (*h*), and 0.7869 for equation (π). The results for each parameter estimate are as follows. The estimated coefficients on the current number of harvesters (*n*) have the expected signs for all three equations and are statistically significant at the 1% confidence level only in equation (*h*), but not significant in equations (*H*) and (π). On the other hand, the parameter estimates for the expected future harvesters (n^e) have the expected signs for all three equations and are statistically significant at the 5% confidence level only in equation (*H*), but not significant in equations (*h*) and (π).

This alternative model is also estimated by 3SLS estimation and the results are presented in Table IV.7. The systems generalized R^2 is again very high (1.0000). The results for all three equations are almost equivalent to the ones in Table IV.6. The estimated coefficients on both the current and future number of harvesters (*n*) still have the expected signs for all three equations.

To summarize, the econometric model based on three equilibrium equations is estimated by equation-by-equation OLS and 3SLS estimation. These two estimations are also used for the alternative specification by dropping the fish stock (*S*) term and adding the expected harvesters term (n^e). The parameter estimates on current number of

Table IV. 6
Parameter estimates by equation-by-equation ordinary least squares (OLS) estimation (adding expected harvesters term and dropping fish stock term)

Variables	Equations (OLS)		
	Log-linear		Semilog
	Collective harvest (H)	Individual harvest (h)	First-period profit (π)
Constant	0.72889 (5.997)	15.405*** (0.7583)	6.3738 (11.36)
Number of harvesters (n)	0.58610 (0.6802)	-0.40451*** (0.08600)	-1.5513 (1.289)
Expected harvesters (n^e)	1.0033 (0.8489)	0.34118** (0.1073)	0.78400 (1.608)
Price of pollock (P)	-0.088687 † (0.4762)	0.62265*** (0.06021)	0.89380 (0.9022)
Average cost (α)	0.0031367 † (0.7542)	-0.91991*** (0.09536)	-1.0296 (1.429)
Discount rate (δ)	-1.0849 † (2.537)	-2.9722*** † (0.3208)	-1.2052 (4.807)
Fish Stock (S)	- -	- -	- -
Dummy (D)	0.26993 (0.7602)	0.014078 (0.09612)	0.14651 (1.440)
R^2	0.9881	0.9987	0.7869
DW	2.9604	3.2349	3.0574

Standard errors are in parentheses.
** Statistically significant at 5 % significance level (one-tailed test with 3 d.f.).
*** Statistically significant at 1 % significance level (one-tailed test with 3 d.f.).
† Unexpected sign.

Table IV. 7
Parameter estimates by three stage least squares (3SLS) estimation (adding expected harvesters term and dropping fish stock term)

Variables	Equations (3SLS)		
	Log-linear		Semilog
	Collective harvest (H)	Individual harvest (h)	First-period profit (π)
Constant	0.49922 (6.060)	15.229*** (0.8021)	6.1904 (11.47)
Number of harvesters (n)	0.54620 (0.6955)	-0.43507*** (0.09207)	-1.5832 (1.316)
Expected harvesters (n^e)	1.0595 (0.8730)	0.38419** (0.1156)	0.82886 (1.652)
Price of pollock (P)	-0.097562† (0.4779)	0.61585*** (0.06326)	0.88671 (0.9044)
Average cost (α)	0.070917† (0.7923)	-0.86801*** (0.1049)	-0.97550 (1.499)
Discount rate (δ)	-1.1841† (2.565)	-3.0481***† (0.3395)	-1.2844 (4.853)
Fish Stock (S)	- -	- -	- -
Dummy (D)	0.29200 (0.7652)	0.030982 (0.1013)	0.16414 (1.448)
R^2	0.9881	0.9986	0.7868
DW	2.9888	2.9435	3.0431

Standard errors are in parentheses.
Systems generalized R^2: 1.0000.
** Statistically significant at 5 % significance level (one-tailed test with 3 d.f.).
*** Statistically significant at 1 % significance level (one-tailed test with 3 d.f.).
† Unexpected sign.

harvesters (n) have expected signs in three equations for all three specifications. Also, these estimates are statistically significant in three equations for the original specification, in two equations for the second specification, dropping fish stock term, and only one equation for the third specification, adding expected harvesters term and dropping fish stock term. On the other hand, the parameter estimates on expected number of harvesters (n^e) in the third specification have expected signs in three equations and are statistically significant only for equation (h), but not for equations (H) and (π). These results of the perfect expected signs support the predictions in propositions IV.1 and IV.2, although some of the results are not statistically significant.

It is important to note, however, that the above results are based on a very small sample size. With a small sample size, it is impossible to correct autocorrelation, which appears to exist. Also, with the extremely small sample size, distributions for 3SLS estimators are not normal, so that the 3SLS estimation may not be an appropriate method for the correction of the simultaneity problems. Nevertheless, the basic conclusion remains robust with correction for the possible simultaneity problem and with alternative specification for the multicollinearily problem.

IV. 7 Discussion of Weakness in the Data and an Alternative Explanation

In the previous section, the empirical results show that the signs of estimated coefficients for the number of current harvesters and the expected number of future harvesters (n and n^e) are consistent with the predictions in proposition IV.1 and IV.2, although some of them are not statistically significant. That is, an increase in the number of harvesters in the current period increases the collective harvest level, but reduces both the individual harvest and profit level. Also, an increase in the expected number of future harvesters increases all three levels.

There are several weakness in the data used in this empirical analysis. The first concern is the economic data. The empirical analysis uses annual economic data (group mean data) from the Japanese *Hokutensen* trawl fishery. These economic data, specifically the average cost data, used between 1982 and 1985 may not be a correct measure. For example, between 1982 and 1985, the *Hokutensen* trawlers did not solely visit the Donut Hole, but combined visits to the Donut Hole, and the Russian and U.S. EEZ. Therefore, the real trip cost for the Donut Hole during this period may be lower than the data used in this study. This causes a measurement error problem: the coefficients on the average cost and the fish stock (CPUE) are inconsistent and biased toward zero (i.e., attenuation) (Greene, 1990, pp. 293-299). As a remedy for this problem, a dummy variable is used in this study (see section IV. 4).

The other concern is the fish stock data. Direct estimates of the pollock stock in the Donut Hole are not available. While the CPUE is used as a proxy of the fish stock in this study, it may not provide a good measure of the stock (this issue is discussed in the section IV. 4 in detail). Also, the pollock stock in the Donut Hole may migrate to the U.S. EEZ or straddle the two areas. In general, the pollock stock in the Donut Hole is considered a straddling stock, while there is a disagreement among different countries' biologists. As a simple case, if some of pollock stock migrate out to the U.S. EEZ after the harvest, then the harvesters in the Donut Hole have less incentive to conserve the fish stock for the future. Hence, the harvest level for each harvester will be relatively larger than the theoretical model would predict in this study (section IV. 3). However, this factor only changes the magnitude not the qualitative effect of the strategic behavior of each harvester, so that the relationship between the number of harvesters, and equilibrium harvest level and resource rent (propositions IV.1 and IV.2) does not change.

There is an alternative theory that is consistent with the patterns between the number of harvesters, and equilibrium harvest level (or fish stock level) and resource rent in the two propositions in this study. Smith (1968) provides the entry and exit model, which is an extended dynamic version of Gordon's (1954) model of rent dissipation. While both models provide a rent dissipation process, Smith's model particularly provides predictions of the dynamic transition paths. If harvesters in a common property fishery earn positive profit, then additional harvesters are attracted to the fishery. Entry will continue until all operating harvesters have zero profit and resource rent is totally dissipated. On the other hand, if harvesters suffer losses because of a reduction of fish stock, some of harvesters exit from the fishery. This will increase fish stock to a profitable level once again. Then, entry will continue until the fishery reaches a bionomic equilibrium of rent dissipation. That is, the Gordon and Smith's entry and exit model show that an increase (decrease) in the number of harvesters will decrease (increase) the fish stock level and lower (raise) profit. These predictions are identical with the ones from the game-theoretic model in this study. Therefore, the empirical analysis in this study simultaneously test the predictions of the entry and exit model as well as the ones of the game-theoretic model.

Chapter V

CONCLUSIONS

This dissertation considers the problems raised by common property fisheries resources. In particular, its inefficiency nature and the effect of the number of harvesters on the optimal harvest choice of each harvester are examined. In Chapter III, these two points are analyzed on a highly migratory fish stocks (HMFS) fishery. A two-period dynamic game model is developed. The model contains two stages in each period, in which the coastal state harvests the fish stock prior to any distant-water fishing (DWF) harvesters. The model is solved for subgame perfect equilibrium, and equilibrium harvest levels and resource rents are derived. These equilibrium solutions are used to examine the effects of DWF entry and of having an exclusive economic zone (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 finds 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 the

Stackelberg model of sequential harvest yields greater equilibrium harvests, given the stock size, than does the Cournot simultaneous harvest model. The 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.

In Chapter IV, an empirical test is conducted for harvesting behaviors in common property fisheries resources. By using the dynamic Cournot oligopoly model of Negri (1990), the effect of the current and future number of harvesters on collective and individual equilibrium harvest levels and equilibrium resource rents is analyzed. The model allows two hypotheses to be tested. One is that an increase in the number of harvesters in a high seas fishery increases the collective equilibrium harvest level by all harvesters, but reduces both the equilibrium harvest level and the resource rent of each harvester. The other is that an increase in the future expectation of the number of harvesters increases all three equilibrium levels.

The hypotheses are tested by using data from the Japanese trawl fishery, especially the *Hokutensen*, which harvested the pollock stock from the Donut Hole in the central Bering Sea between 1982 and 1991. The empirical results show that all the parameter estimates for the current and future number of harvesters are of the predicted sign in all three equilibrium equations, although they are not all statistically significant (this may be due to the small sample). That is, the empirical results provide some evidence that the Japanese trawl harvesters (the *Hokutensen* trawlers) operated the high seas fishery by responding to the current and future number of harvesters in the Donut Hole.

While the above empirical results are consistent with dynamic Cournot game theory, some caution should be used in interpreting the empirical results. The estimations in this study are based on a very small sample size, so the results may not be statistically reliable. Also, the data used in this study are average sample data from the Japanese *Hokutensen* trawlers only. Moreover, direct measurement of the pollock stock in the Donut Hole is not available.

Finally, further analyses are suggested as follows. For the theoretical analysis, the two-period model could be extended to an infinite-horizon model. In this model, both the approach path and the steady-state equilibrium solution could be analyzed. Also, social welfare could be examined by including market power considerations in the model. Moreover, another type of game model would be required for the analysis of straddling fish stocks, which is also a great concern at the present. In the case of straddling fish stocks, it is uncertain how many fish migrate out from a coastal state EEZ. Hence, the model might be constructed by including a probability on the fish migration, and solved for a perfect Bayesian equilibrium.

For the empirical analysis, it is essential to collect more data to obtain more statistically reliable results. For example, it may be possible to obtain a pooled data set that is not just the average of the all the *Hokutensen* harvesters but rather each individual harvester, or a data set for other countries' trawl harvesters (i.e., South Korea or Poland). These analyses will have to be left for future research.

BIBLIOGRAPHY

Adelman, M. 1986a. Scarcity and World Oil Prices. *Review of Economics and Statistics* 68: 387-397.

Adelman, M. 1986b. The Competitive Floor to World Oil Prices. *Energy Journal* 7: 9-23.

Berndt, E. R. 1991. *The Practice of Econometrics: Classic and Contemporary*. Addison-Wesley Publishing Company, Inc. Massachusetts.

Canfield, J. L. 1993. Recent Developments in Bering Sea Fisheries Conservation and Management. *Ocean Development and International Law* 24: 257-289.

Chiarella, C., M. C. Kemp, N. V. Long, and K. Okuguchi. 1984. On the Economics of International Fisheries. *International Economic Review* 25: 85-92.

Clark, C. W. 1980. Restricted Access to Common-Property Fishery Resources: A Game Theoretic Analysis. in *Dynamic Optimization and Mathematical Economics*, P. Liu, ed., New York: Plenum Press, pp. 117-132.

Clark, C. W. 1990. *Mathematical Bioeconomics: The Optimal Management of Renewable Resources*. 2nd edition, Wiley-Interscience, New York.

Clarke, F. H. and G. R. Munro. 1987. Coastal States, and Distant Water Fishing Nations and Extended Jurisdiction: A principal-agent analysis. *Natural Resource Modeling* 2(1): 81-107.

Clarke, F. H. and G. R. Munro. 1991. Coastal States and Distant Water Fishing Nations: Conflicting Views of the Future. *Natural Resource Modeling* 5(3): 345-369.

Conniffe, D. 1982. A Note on Seemingly Unrelated Regressions. *Econometrica* 50: 229-233.

Dahl, C. and M. Yucel. 1991. Dynamic Modelling and Testing of OPEC Behavior. *Energy Journal*.

Ehtamo, H. and R. P. Hämäläinen. 1993. A Cooperative Incentive Equilibrium for a Resource Management Problem. *Journal of Economic Dynamics and Control* 17: 659-678.

Eswaran, M. and T. R. Lewis. 1984. Appropriability and the Extraction of a Common Property Resources. *Economica* 51: 393-400.

Eswaran, M. and T. R. Lewis. 1985. Exhaustible resources rights and alternative equilibrium concept. *Canadian Journal of Economics* 18(3): 459-473.

Ferrara, I. and P. C. Missios. 1997. Transboundary Renewable Resource Management: A Dynamic Game with Differing Non-Cooperative Payoffs. *Marine Resource Economics*, forthcoming.

Fischer, R. D. and L. J. Mirman. 1992. Strategic Dynamic Interaction: Fish Wars. *Journal of Economic Dynamics and Control* 16: 267-287.

Fischer, R. D. and L. J. Mirman. 1996. The Complete Fish Wars: Biological and Dynamic Interactions. *Journal of Environmental Economics and Management* 30: 34-42.

Fudenberg, D. and J. Tirole. 1993. *Game Theory*, the MIT Press, Cambridge, Massachusetts, London, England.

Gibbons, R. 1992. *Game Theory for Applied Economists*, Princeton University Press, Princeton, New Jersey.

Gordon, H. S. 1954. The Economic Theory of a Common Property Resource: The Fishery. *Journal of Political Economy* 62: 124-142.

Greene, W. H. 1990. *Econometric Analysis*, Macmillan Publishing Company, New York.

Griffin, J. 1985. OPEC Behavior. *American Economic Review* 75: 954-963.

Hannesson, R. 1995. Fishing on the High Seas: Cooperation or Competition? *Marine Policy* 19(5): 371-377.

Hannesson, R. 1997. Fishing as a Supergame. *Journal of Environmental Economics and Management* 32: 309-322.

Hayashi, M. 1991. Fisheries in the North Pacific: Japan at a Turning Point. *Ocean Development and International Law* 22: 343-364.

Intriligator, M. D. 1971. *Mathematical Optimization and Economic Theory*. Pentice-Hall, Inc., Englewood Cliffs, N.J.

Judge, G. G., W. E. Griffiths, R. C. Hill, H. Lutkepohl and T. C. Lee. 1988 *Introduction to the Theory and Practice of Econometrics*, 2nd ed. New York: John Wiley.

Kaitala, V. T., R. P. Hämäläinen, and J. Ruusunen. 1985. On the Analysis of Equilibria and Bargaining in a Fishery Game. in *Optimal Control Theory and Economic Analysis 2*, G. Feichtinger ed., North-Holland: Elsevier, pp. 593-606.

Kaitala, V. T. and M. Pohjola. 1988. Optimal Recovery of a Shared Resource Stock: A Differential Game with Efficient Memory Equilibria. *Natural Resource Modeling* 3(1): 91-119.

Kaitala, V. T. and G. R. Munro. 1993. The Management of High Seas Fisheries. *Marine Resource Economics* 8: 313-329.

Kamien, M. I. and N. L. Schwartz. 1991. *Dynamic Optimization: The Calculus of Variations and Optimal Control in Economics and Management*, 2nd ed., North-Holland.

Karp, L. 1992. Social Welfare in a Common Property Oligopoly. *International Economic Review* 33: 353-372.

Kemp, M. C. and N. V. Long. 1980. Resource Extraction under Conditions of Common Access. in *Exhaustible Resources, Optimality and Trade*, eds. M. C. Kemp and N. V. Long, Amsterdam, North Holland.

Kennedy, J. O. S. 1987. A Computable Game Theoretic Approach to Modeling Competitive Fishing. *Marine Resource Economics* 4: 1-14.

Kennedy, J. O. S. and H. Pasternak. 1991. Optimal Australian and Japanese Harvesting of Southern Bluefin Tuna. *Natural Resource Modeling* 5(2): 213-238.

Levhari, D. and L. J. Mirman. 1980. The Great Fish War: An Example Using a Dynamic Cournot-Nash Solution. *Bell Journal of Economics* 11: 322-334.

Mason, C. F. and S. Polasky. 1994. Entry Deterrence in the Commons. *International Economic Review* 35: 507-525.

Mason, C. F. and S. Polasky. 1997. The Optimal Number of Firms in the Commons: A Dynamic Approach. *Canadian Journal of Economics*, forthcoming.

McMillan, J. and H.-W. Sinn. 1980. Oligopolistic Extraction of a Common-Property Resource: Dynamic Equilibria. in *Exhaustible Resources, Optimality and Trade*, eds. M. C. Kemp and N. V. Long, Amsterdam, North Holland.

Missios, P. C. and C. G. Plourde. 1996. The Canada-European Union Turbot War: A Brief Game Theoretic Analysis. *Canadian Public Policy* 22(2): 144-150.

Missios, P. C. and C. G. Plourde. 1997. Transboundary Renewable Resource Management and Conservation Motives. *Marine Resource Economics*, forthcoming.

Mito, K. 1993. When is the reopening of the pollock fishery in the Bering Sea? *Enyo* 93: 2-6.

Mohr, E. 1988. Appropriation of Common Access Natural Resources Through Exploration: The Relevance of the Open-Loop Concept. *International Economic Review* 29(2): 307-320.

Munro, G. R. 1979. The Optimal Management of Transboundary Renewable Resources. *Canadian Journal of Economics* 12: 355-376.

Munro, G. R. 1987. The Management of Shared Fishery Resources Under Extended Jurisdiction. *Marine Resource Economics* 3(4): 271-296.

Munro, G. R. 1996. Approaches to the Economics of the Management of High Seas Fishery Resources: A Summary. *Canadian Journal of Economics* 29: S157-S164.

Naito, T. and S. Polasky. 1997. Analysis of a Highly Migratory Fish Stocks Fishery: A Game Theoretic Approach. *Marine Resource Economics*, forthcoming.

Nash, J. F. 1950. The bargaining problem. *Econometrica* 18: 155-62.

Negri, D. H. 1990. Strategy of the Commons. *Natural Resource Modeling* 4(4): 521-537.

Plourde, C. G. and D. Yeung. 1989. Harvesting of a Transboundary Replenishable Fish Stock: A Noncooperative Game Solution. *Marine Resource Economics* 6: 57-70.

Polasky, S. 1992. Do Oil Producers Act as 'Oil'igopolists? *Journal of Environmental Economics and Management* 23: 216-247.

Reinganum, J. F. 1985. Corrigendum. *Journal of Economic Theory* 35: 196-197.

Reinganum, J. F. and N. L. Stokey. 1985. Oligopoly Extraction of a Common Property Natural Resource: The Importance of the Period of Commitment in Dynamic Games. *International Economic Review* 26(1): 161-173.

Schaefer, M. B. 1954. Some Aspects of the Dynamics of Populations Important to the Management of Commercial Marine Fisheries. *Bulletin of the Inter-American Tropical Tuna Commission* 1: 25-56.

Selten, R. 1965. Spieltheoretische Behandlung eines Oligopolmodells mit Nachfrageträgheit, *Zeitschrift für die gesamte Staatswissenschaft*, vol.12, pp. 301-324.

Smith, V. L. 1968. Economics of Production from Natural Resources. *American Economic Review* 58: 409-431.

Stackelberg, H. von. 1934. *Marktform und Gleichgewitcht*, Vienna: Julius Springer.

Tirole, J. 1988. *The Theory of Industrial Organization.* The MIT Press, Massachusetts Institute of Technology, Cambridge, Massachusetts.

United Nations. 1982. United Nations Conference on the Law of the Sea. *United Nations Document* A/Conf. 61/122.

Vislie, J. 1987. On the Optimal Management of Transboundary Renewable Resources: A Comment on Munro's Paper. *Canadian Journal of Economics* 20(4): 870-875.

APPENDICES

Appendix A

Proofs of Propositions

***Proof of Proposition III.1*:**

Consider first the partial derivative of Φ in (III.14) and Ψ in (III.17) with respect to a parameter n (the number of DWF harvesters). These sings can be shown 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, it can be shown:

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

Then, by using (A2), the signs of the partial derivatives of the equilibrium harvest level with respect to n for the coastal state can be shown as

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

and, by using (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 the 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:

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

Substituting (A2) into this equation gives:

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

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

Manipulating Ψ gets:

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

Then, by substituting (A7) into equation (A6), the sign of the partial derivative is finally shown as

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

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

Proof of Proposition III.2:

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

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

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

$$=-\left\{\frac{\partial \Phi}{\partial n}\frac{n}{n+1}+\frac{\Phi}{(n+1)^2}\right\}\left(1-\Psi\frac{P}{2\alpha}\right)\frac{\beta P^3}{4\alpha^2}S_1<0, \tag{A9}$$

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

To show the sign of the partial derivative of the two-period optimal value function for the DWF harvesters in (III.20), for simplicity, 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:

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

Only the sign of the partial derivative of A with respect to n in (A11) is considered since the second term is negative. Taking partial derivative of A with respect to n gets:

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

$$-\left\{(n+1)\Phi-n\Phi^2\right\}\frac{\partial \Psi}{\partial n}\frac{P}{2\alpha}-\frac{\partial \Psi}{\partial n}\left(1-\frac{P}{2\alpha}\right)\left(1-\Psi\frac{P}{2\alpha}\right)\frac{\beta P}{2\alpha}. \tag{A12}$$

Since the third and last terms are negative by (A2), we consider only the signs of the first and second terms. Manipulating these two terms and using (A2), it can be shown that they are non-positive:

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

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

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

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

$$=-(n-1)\frac{\partial\Phi}{\partial n}\left[\Phi+\left(1-\frac{P}{2\alpha}\right)\frac{\beta P}{(n+1)\alpha}\right]\left(1-\Psi\frac{P}{2\alpha}\right)\leq 0, \tag{A13}$$

where the equality holds as $n = 1$. By (A11), (A12), and (A13), therefore, the sign of the partial derivative can be shown as

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

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

***Proof of Proposition III.3*:**

The bionomic equilibrium harvest level for the coastal state in Section 3 has been already shown, which is a positive value. Now, that for DWF harvesters is considered. 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 (III.20) gives:

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

Then, by taking the limit on n for equation (A16) and using (A15), the bionomic equilibrium harvest level can be show as

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

which completes the proof of the proposition III.3.

***Proof of Proposition IV.1*:**

For simplicity, we first let:

$$\Theta = 1 - \frac{1}{(n+1)^2}\frac{\beta P}{\alpha},$$

so that the corrective equilibrium harvest level, individual equilibrium harvest level, and two-period optimal value function are, respectively :

$$H_1^* = \frac{n}{n+1}\Theta\frac{P}{\alpha}S_1, \tag{A18}$$

$$h_1^{i*} = \frac{1}{n+1}\Theta\frac{P}{\alpha}S_1, \text{ and} \tag{A19}$$

$$\pi_1^{i*} = \frac{1}{n+1}\left(\Theta - \frac{n}{n+1}\Theta^2\right)\frac{P^2}{\alpha}S_1. \tag{A20}$$

Consider first the partial derivative of Θ with respect to a parameter n (the number of harvesters). We can show its sing as follows:

$$\frac{\partial\Theta}{\partial n} = \frac{2}{(n+1)^3}\frac{\beta P}{\alpha} > 0. \tag{A21}$$

Then, by using (A21), we can show the sign of the partial derivative of the collective equilibrium harvest level with respect to n:

$$\frac{\partial H_1^*}{\partial n} = \left[\frac{1}{(n+1)^2}\Theta + \frac{n}{n+1}\frac{\partial\Theta}{\partial n}\right]\frac{P}{\alpha}S_1 > 0. \tag{A22}$$

Also, the partial derivative of the individual equilibrium harvest with respect to the parameter n is:

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

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

$$= \left[-\frac{1}{(n+1)^2} + \frac{3}{(n+1)^4}\frac{\beta P}{\alpha}\right]\frac{P}{\alpha}S_1$$

$$= -\frac{1}{(n+1)^2}\left[1 - \frac{3}{(n+1)^2}\frac{\beta P}{\alpha}\right]\frac{P}{\alpha}S_1 < 0, \tag{A23}$$

since the terms in the brackets are positive ($n \geq 1$).

Taking the partial derivative of (A20) with respect to n gives:

$$\frac{\partial\pi_1^{i*}}{\partial n} = -\frac{1}{(n+1)^2}\Theta + \frac{1}{n+1}\frac{\partial\Theta}{\partial n} + \frac{n-1}{(n+1)^3}\Theta^2 - \frac{2n}{(n+1)^2}\Theta\frac{\partial\Theta}{\partial n}$$

$$= -\left(1 - \frac{n-1}{n+1}\Theta\right)\Theta - \frac{1}{n+1}\left(\frac{2n}{n+1}\Theta - 1\right)\frac{\partial\Theta}{\partial n}$$

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

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

$$= -\left(1-\frac{n-1}{n+1}\Theta\right)\Theta - \frac{1}{(n+1)^2}\left[n-1+\frac{1}{(n+1)}\frac{\beta P}{\alpha}\right]\frac{\partial\Theta}{\partial n}. \quad \text{(A24)}$$

By (A21) and (A24), we can finally show:

$$\frac{\partial \pi_1^{i*}}{\partial n} < 0. \quad \text{(A25)}$$

Hence, by (A22), (A23), and (A25), the proposition IV.1 holds.

***Proof of Proposition IV.2*:**

Taking the partial derivative of the collective equilibrium harvest in equation (IV.15) with respect to n_1 and n_2 gives, respectively as

$$\frac{\partial H_1^*}{\partial n_1} = \frac{1}{n_1+1}\left[1-\frac{1}{(n_2+1)^2}\frac{\beta P}{\alpha}\right]\frac{P}{\alpha}S_1 > 0 \text{ and} \quad \text{(A26)}$$

$$\frac{\partial H_1^*}{\partial n_2} = \frac{n_1}{n_1+1}\left[\frac{2}{(n_2+1)^3}\frac{\beta P}{\alpha}\right]\frac{P}{\alpha}S_1 > 0. \quad \text{(A27)}$$

Also, taking the partial derivative of the individual equilibrium harvest in equation (IV.16) with respect to n_1 and n_2 gives, respectively as

$$\frac{\partial h_1^{i*}}{\partial n_1} = -\frac{1}{(n_1+1)^2}\left[1-\frac{1}{(n_2+1)^2}\frac{\beta P}{\alpha}\right]\frac{P}{\alpha}S_1 < 0 \text{ and} \quad \text{(A28)}$$

$$\frac{\partial h_1^{i*}}{\partial n_2} = -\frac{1}{(n_1+1)}\left[\frac{2}{(n_2+1)^3}\frac{\beta P}{\alpha}\right]\frac{P}{\alpha}S_1 > 0. \quad \text{(A29)}$$

Finally, the partial derivative of the individual first-period profit in equation (IV.17) with respect to n_1 and n_2 can be derived, respectively as

$$\frac{\partial \pi_1^{i*}}{\partial n_1} = \left[-\frac{1}{(n_1+1)^2}\left(1-\frac{1}{(n_2+1)^2}\frac{\beta P}{\alpha}\right) - \frac{n_1-1}{(n_1+1)^3}\left(1-\frac{1}{(n_2+1)^2}\frac{\beta P}{\alpha}\right)^2\right]\frac{P^2}{\alpha}S_1 < 0 \text{ and} \quad \text{(A30)}$$

$$\frac{\partial \pi_1^{i*}}{\partial n_2} = \left[\frac{1}{(n_1+1)}\left(\frac{2}{(n_2+1)^3}\frac{\beta P}{\alpha}\right) - \frac{1}{(n_1+1)^2}\left(\frac{2}{(n_2+1)^3}\frac{\beta P}{\alpha}\right)\left(1-\frac{1}{(n_2+1)^2}\frac{\beta P}{\alpha}\right)^2\right]\frac{P^2}{\alpha}S_1$$

$$= \frac{1}{(n_1+1)}\left(\frac{2}{(n_2+1)^3}\frac{\beta P}{\alpha}\right)\left[1-\frac{2n_1}{(n_1+1)^2}\left(1-\frac{1}{(n_2+1)^2}\frac{\beta P}{\alpha}\right)\right]\frac{P^2}{\alpha}S_1 > 0. \quad \text{(A31)}$$

Therefore, by (A26) through (A31), the proposition IV.2 holds.

Appendix B

Derivations of the Signs for Parameters

Price level, P:

$$\frac{\partial H_1^*}{\partial P}=\frac{n}{n+1}\left[\frac{\partial\Theta}{\partial P}\frac{P}{\alpha}+\Theta\frac{1}{\alpha}\right]S_1$$

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

$$=\frac{n}{n+1}\left[1-\frac{2}{(n+1)^2}\frac{\beta P}{\alpha}\right]\frac{1}{\alpha}S_1>0.$$

$$\frac{\partial h_1^{i*}}{\partial P}=\frac{1}{n+1}\left[1-\frac{2}{(n+1)^2}\frac{\beta P}{\alpha}\right]\frac{1}{\alpha}S_1>0.$$

$$\frac{\partial V_1^{i*}}{\partial P}=\frac{1}{(n+1)^2}\left[\frac{\partial K}{\partial P}\frac{P^2}{\alpha}+2K\frac{P}{\alpha}\right]S_1=\frac{1}{(n+1)^2}\left[\frac{\partial K}{\partial P}P+2K\right]\frac{P^2}{\alpha}S_1>0,$$

where $\left[\frac{\partial K}{\partial P}P+2K\right]$

$$=\left(1-\frac{2}{(n+1)^2}\frac{\beta P}{\alpha}\right)\left(1-\frac{n^2}{(n+1)^2}\frac{\beta P}{\alpha}\right)-\Theta\left(1-\frac{2n^2}{(n+1)^2}\frac{\beta P}{\alpha}\right)+2\beta(1+r)>0.$$

Cost parameter, α:

$$\frac{\partial H_1^*}{\partial \alpha}=\frac{n}{n+1}\left[\frac{\partial\Theta}{\partial \alpha}\frac{P}{\alpha}-\Theta\frac{P}{\alpha^2}\right]S_1$$

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

$$=-\frac{n}{n+1}\left[1-\frac{2}{(n+1)^2}\frac{\beta P}{\alpha}\right]\frac{P}{\alpha^2}S_1<0.$$

$$\frac{\partial h_1^{i*}}{\partial \alpha}=-\frac{1}{n+1}\left[1-\frac{2}{(n+1)^2}\frac{\beta P}{\alpha}\right]\frac{P}{\alpha^2}S_1<0.$$

$$\frac{\partial V_1^{i*}}{\partial \alpha}=\frac{1}{(n+1)^2}\left[\frac{\partial K}{\partial \alpha}\frac{P^2}{\alpha}-K\frac{P^2}{\alpha^2}\right]S_1=\frac{1}{(n+1)^2}\left[\frac{\partial K}{\partial \alpha}+\frac{K}{\alpha}\right]\frac{P^2}{\alpha}S_1<0,$$

where $\left[\frac{\partial K}{\partial \alpha}+\frac{K}{\alpha}\right]$

$$=\left[-\left(1-\frac{2}{(n+1)^2}\frac{\beta P}{\alpha}\right)\left(1-\frac{n^2}{(n+1)^2}\frac{\beta P}{\alpha}\right)-\beta\left(1-\frac{n^2}{(n+1)^2}\frac{P}{\alpha}\Theta\right)-\beta r\right]\frac{1}{\alpha}<0.$$

Discount factor, β:

$$\frac{\partial H_1^*}{\partial \beta} = -\frac{n}{(n+1)^3}\frac{P^2}{\alpha^2}S_1 < 0$$

$$\frac{\partial h_1^{i*}}{\partial \beta} = -\frac{1}{(n+1)^3}\frac{P^2}{\alpha^2}S_1 < 0.$$

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

Fish stock level, S:

$$\frac{\partial H_1^*}{\partial S} = \frac{n}{n+1}\Theta\frac{P}{\alpha} > 0.$$

$$\frac{\partial h_1^{i*}}{\partial S} = \frac{1}{n+1}\Theta\frac{P}{\alpha} > 0.$$

$$\frac{\partial V_1^{i*}}{\partial S} = \frac{1}{(n+1)^2}\left[\left(1 - \frac{n^2}{(n+1)^2}\frac{\beta P}{\alpha}\right)\Theta + \beta(1+r)\right]\frac{P^2}{\alpha} > 0.$$

Appendix C

Sources of Data

Dependent variables

(1) collective pollock harvest (H):
Annual Fishery Report [Suisan Nenkan] by the Fisheries Agency of Japan (1996).

(2) individual harvest of pollock (h):
Annual Statistical Report of Fishery and Aquaculture Production [Gyogyo, Yosyokugyo Seisan Tokei Nenpo] by the Department of Statistics and Information, Ministry of Agriculture, Forestry and Fishery (Japan), 1982-1991.

(3) individual harvester's profit (π):
Investigation Report of Fishery Economics [Gyogyo Keizai Chosa Hokoku] by the Department of Statistics and Information, Ministry of Agriculture, Forestry and Fishery (Japan), 1982-1991.

Explanatory variables

(4) number of harvesters (n and n^e):
Hayashi (1991);
Canfield (1993); and
Annual Fishery Report [Suisan Nenkan] by the Fisheries Agency of Japan (1996).

(5) price of the harvested pollock (P):
Annual Statistical Report of Fishery Product Market [Suisanbutsu Ryutsu Tokei Nenpo] by the Department of Statistics and Information, Ministry of Agriculture, Forestry and Fishery (Japan), 1982-1991.

(6) discount rate (δ):
Economic Statistics Annual [Keizai Tokei Nenpo] by the Research and Statistics Department, Bank of Japan, 1994.

(7) cost parameter (average cost) (α):
Investigation Report of Fishery Economics [Gyogyo Keizai Chosa Hokoku] by the Department of Statistics and Information, Ministry of Agriculture, Forestry and Fishery (Japan), 1982-1991.

(8) fish stock (catch per unit effort) (S):

Investigation Report of Fishery Economics [Gyogyo Keizai Chosa Hokoku] by the Department of Statistics and Information, Ministry of Agriculture, Forestry and Fishery (Japan), 1982-1991.

Instrumental variables

(9) price of surimi:

Annual Statistical Report of Fishery Product Market [Suisanbutsu Ryutsu Tokei Nenpo] by the Department of Statistics and Information, Ministry of Agriculture, Forestry and Fishery (Japan), 1982-1991.

(10) price of heavy fuel oil A:

Price Indexes Annual [Bukka Shisu Nenpo] by the Research and Statistics Department, Bank of Japan, 1992.

(11) national income:

Annual Report on National Accounts [Kokumin Keizai Keisan Nenpo] by the Economic Planning Agency (Japan), 1994.

(Note that the English titles for the Japanese publications in this section are translated from Japanese by the author. The original Japanese titles are in brackets.)