Intermediate Market Power as a Mechanism for Managing Common-Pool Resources

by

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Abstract

Common pool resources present a challenging problem for management institutions. The tragedy of the commons, the externality associated with common pool resources, results in inefficient competitive equilibria. The over-exploitation of scarce resources and over-investment by resource extractors are a result of this externality. Fisheries are a commonly cited case study for this phenomenon. Expanding on the past work illustrating how monopolistic market power can result in more efficient outcomes than open-access regimes, this paper describes the theoretical impacts of intermediate levels of market power in fisheries. By modeling Cournot competition in a theoretical fishery, I compare the steady-state outcomes of a social planner, monopolist, and oligopoly. The findings of this analysis suggest that there always exists an N-firm oligopoly that has a steady-state stock and harvest that is indistinguishable from a welfare-maximizing social planner.

Keywords: Market Power, Common Pool Resources, Fisheries Management, Resource Economics

Contents

Introduction

It is well understood among resource regulators that sole ownership of a resource will yield the first-best outcome. In fisheries, a sole owner has no incentive to race for fish and internalizes the dynamic costs associated with increased harvesting in each period. Without sole ownership, an open-access regime results in the over-exploitation of fish stocks and over-investment in fishing activities. This externality, present in markets for all common-pool resources, is called the tragedy of the commons. Allowing for sole ownership of a resource avoids this externality. As a result of an increased understanding of fisheries dynamics and the externalities associated with open-access regimes, rights-based management methods are commonplace in modern fisheries. Assuming firms are price takers, rights-based ownership mechanisms result in fisheries reaching first-best social outcomes. However, if harvesters are not price takers and can influence market prices, sole ownership no longer leads to the first-best outcome. In large commercial fisheries that face global competition and international trade, it is unlikely that a single vessel can set prices as certain fish stocks are a global commodity. However, in small fisheries producing high-quality fresh fish or serving a local market without substitutes, a downward-sloping demand curve exists (Manning and Uchida, 2016).

In the case of non-renewable resources, there is extensive research into the impacts monopolistic market power has on production. A monopolist acts as a conservationist, producing less than the first-best production path to maximize profits (Stiglitz 1976; Hotelling 1931). Manning and Uchida (2016) examine a dynamic fishery model and describe the market-wide impacts of monopoly ownership. They demonstrate that a monopolist restricts harvests and maintains a higher stock in a fishery compared to the first-best outcome and can arrive at a steady state which provides greater total welfare than the steady-state level of harvest reached by an open-access regime. Manning and Uchida identify that with market power, monopolistic ownership can serve as a second-best outcome. This second-best outcome is closest to the social planner's first-best result with highly elastic demand and costs that are highly responsive to stock levels.

In this paper, I extend the analysis performed by Manning and Uchida (2016) and define the steady-state outcomes for levels of intermediate market power. I compare the optimal harvesting path and steady-state equilibrium of a Cournot oligopoly with those of a monopolist, social planner, and an open-access regime. I find that there always exists a concentration of market power that equates the Cournot oligopoly's steady-state equilibrium with that of a social planner.

The Tragedy of the Commons

The externality associated with common pool resources is called the tragedy of the commons. When producers have open access to a common pool resource, this externality results in significant welfare losses for rational decision-makers. The tragedy of the commons is one explanation for why we observe excessive traffic, pollution, and soil erosion. It also explains why many fisheries have endangered populations. When agents taking rational actions impose external costs on other market agents, this externality appears.

A simple example of this externality is metropolitan traffic. When commuters drive to work, they weigh the cost and time of driving against other forms of travel. Individual commuters do not consider the impact that the addition of their vehicle has on all other drivers. Adding one vehicle to the road slows down all other cars, creating an external cost. When thousands of commuters make this calculation, the benefits of driving versus other forms of travel disappear. This externality explains why we observe overcrowded roadways in large metropolitan areas.

In the case of fisheries, this externality is two-fold. First, a 'race to fish' among competing firms is present. Fishing from a high stock level is less costly than fishing from a low stock level. The firm that catches fish first expends less effort per catch and is more profitable. Firms competing to earn more profit will race to catch fish first, resulting in over-investment in fisheries. Additionally, when one firm harvests more today, fewer fish are available in all future periods. This intertemporal effect negatively impacts all firms harvesting from the stock of fish, not only the firm choosing to increase its harvest. Like the simple case of metropolitan traffic, this leads to a depletion of resources value. It explains why we observe high-cost fisheries which maintain low stocks of fish. If the demand for a species is high enough, this same process can lead rational firms to harvest fish stocks to extinction.

Fisheries Management

Over the last one hundred years, fisheries management has evolved several techniques to reduce the impact of the tragedy of the commons. With technological advancements, globalization, and an increased understanding of biology, humans are increasingly skilled at harvesting fish species. An increased ability to catch fish and bring landed fish to consumers led to the over-exploitation of countless fish species. Although the over-exploitation of fish species is not new to the world in the last century, the scale of fisheries and the number of impacted species has increased dramatically. These changes have led governments and management institutions to implement restrictions to protect fisheries from over-exploitation, over-investment, bycatch, the race for fish, and high grading. The traditional mechanisms used by management institutions are restrictions on equipment, time or seasons, and quotas. Each of these methods solves one or many of the problems present in modern fisheries.

Equipment restrictions are often implemented in fisheries when bycatch is a serious issue. Bycatch refers to the unintentional capture of non-target species or non-marketable fish during the harvest of target species. Restricting which equipment can be used by harvesting firms can help reduce the amount of bycatch. In fisheries where trawling or gillnetting is a common practice, bycatch and environmental damage are a concern. Enforcing restrictions on the size, weight, and gauge of netting, fisheries can protect non-target species and reduce bycatch. As with all management practices, equipment restrictions are only effective if they are easily enforceable. Enforcing the size of a vessel may be easily observed by a management institution and by competing firms. However, restrictions on hooks, types of bait, and netting size are more difficult to observe. These restrictions require investment from management institutions to enforce. In Canada and many fisheries globally, restrictions on equipment limit bycatch and environmental damage. However, gear restrictions play little or no role in reducing overall harvest to stop the over-exploitation of target species. Equipment restrictions are effective when used together with other management methods to protect the environment and reduce bycatch.

Fishery managers implement seasonal restrictions for one of two reasons. To reduce total harvest or to protect species during times when they are particularly fragile. Historically, the use of seasonal restrictions to reduce total catch has failed. One of the first fisheries to introduce modern management techniques, the Alaskan Halibut fishery, faced serious over-exploitation throughout the twentieth century. Fisheries managers initially introduced time restrictions in hopes of reducing total catch. The season would end when a certain number of landings had reached the harbour. Vessels raced to catch fish as quickly as possible to maximize profits before the end of the season. Ultimately, the fishing season was reduced to a handful of twenty-four-hour periods each year. Catching as many halibut as possible in a single day, fishermen regularly risked their lives in dangerous conditions to profit before the season closed. These short fishing seasons, named The Halibut Derby, increased the over-exploitation of Alaskan halibut and induced over-investment in the halibut fishery. To remedy the problems created by seasonal restrictions in the Alaskan halibut fishery, managers changed strategies and implemented some of the first North American Individually Transferable Quota's (ITQ's) in 1995 (King 2009). In other fisheries, seasonal fishing occurs naturally, as species congregate in easily accessible places for short periods, such as salmon returning to rivers to spawn. Today, seasonal restrictions protect species during vulnerable periods or appear where seasonal catches naturally occur. They are rarely the sole mechanism for restricting total catch.

Quotas are the most common management technique used to limit harvest in fisheries. Managers mandate a specified amount of harvesting, either for the whole fishery or for each vessel. In theory, quotas stop the over-exploitation of fish species.

Problems arise with fishery-wide quotas that create a race for fish, such as the Halibut Derby in Alaska. Although fishery-wide quotas reduce over-exploitation, they often create incentives to over-invest in fishing activities for short periods, negatively impacting welfare outcomes. More recently, ITQ's have become the favoured method of fisheries management. ITQ's are per vessel quotas which can be bought and sold between vessels, similar to cap-and-trade programs for pollution. Each vessel receives an individual quota, reducing the incentive to catch fish quickly. With no incentive to race for fish firms reduce investment in fishing activity. Markets for ITQ's allow more efficient vessels to buy quota limits from less efficient vessels. Only the most efficient vessels remain in the fishery, further reducing the average cost of harvesting. ITQ's have been a successful tool used widely in fisheries management. Reducing over-investment in fishing activities, over-exploitation of species, and avoiding the race for fish that other management techniques induce. When implemented successfully and policed correctly, ITQ's create a fishing industry that functions the same way an individual social planner would operate.

Literature Review

Over the past 50 years, ITQ's have become generally accepted as a best practice in fisheries management because they provide individuals a right to a portion of the resource, alleviating the commons problem. Although ITQs are a relatively new management mechanism, by 2005, over 10% of ocean fish harvested were taken under ITQ's (Arnason 2005). First implemented in the early 1970s, ITQ's have led to decreased fishing efforts, increased fish stocks, and increased the value of harvests. Although management institutions using ITQ's have seen success, several researchers are critical of ITQ's and similar management systems. The critiques of ITQ's fall into one of two categories. Problems with property rights and the cost of enforcement.

Arnson (2005) critically discusses ITQ's and the underlying theory that drives them. In his critique, Arnson points out that an ITQ is an extraction right, not a property right. A property right grants the owner complete control of the resource in question; an extraction right limits the owner's ability to manage a resource. Consider a cattle farm. A farmer owns the cattle, the land the cattle live on, the food the cattle eat, and the capital necessary to operate the farm. No outside agents control the way the farmer chooses to harvest. In the case of fisheries, an ITQ holder has no control over these additional inputs. An ITQ owner cannot tell other ITQ holders when and where to fish, cannot stop naturally occurring predator-prey relationships, and cannot prevent cities from dumping sewage in nearby waters. All of these forms of interference would be controllable by an owner with full property rights. Arnson argues that the limits to the rights of an ITQ holder create inefficiencies and are inherently sub-optimal. The nature of fisheries and other marine resources means that ITQ's are currently one of the best available options for providing ownership rights in a fishery.

The second argument against ITQ based fisheries is the cost of management. An ITQ system, if followed by all quota holders and developed such that the total annual quota equals the optimal harvest, will result in a socially optimal level of harvest. However, if quota owners have incentives to deviate from their quotas, the optimal outcome is not achieved. It is then necessary for resource managers to monitor and enforce ITQ limits. Additionally, resource managers must update quota limits and monitor stock levels to ensure the optimal quota limits over time. Anderson (1989) discusses the importance of accounting for the cost of management mechanisms when selecting fisheries policies. In some fisheries, with few easily observable vessels and well-understood biology, management and enforcement costs remain low. However, in large fisheries, with many quota holders, difficult to observe harvests, and biological factors that are not well-understood, management and enforcement costs are are high. Additional factors may influence the total cost of a management policy for fisheries. If a policy is complex, firms have a difficult time following them, requiring higher enforcement costs. If policies are frequently changing, it may be costly to communicate changes to firms. Anderson (1989) identifies that simple policies with easily observable, enforceable, and communicable requirements are likely to be best. Even if the policy does not result in the socially optimal harvest, a significant reduction in additional management costs can make it preferable. In the case of ITQ's, fisheries with small fleets and easily observable harvest are inexpensive to manage. However, there may be cases where the cost of coordination, communication, and enforcement outweigh the benefits of having a socially optimal harvest. Begging the question, are there management mechanisms that can outperform ITQ's?

The mechanism or management system yet to be discussed is often described as cooperative management. By allowing all firms operating in a fishery to cooperate, they act as a single entity. There are examples of fishing cooperatives in North America, Japan, and rural communities throughout the developing world (FAO 2012, Manning Uchida 2016). By coordinating efforts, cooperative groups act like a cartel or monopolist. These groups avoid the tragedy of the commons by operating as the sole owner of a resource. Sole owners internalize all costs within the fishery, eliminating the race-to-fish and the dynamic external costs that lead to inefficiencies. Additionally, cooperatives effectively align firms' incentives with those of the larger group they require little or no outside enforcement. The appearance of cooperative groups has spurred further research into the impacts of sole ownership and market power in fisheries.

Clark (1990) describes the dynamic harvesting path of a monopolist in a fishery. He finds that a monopolist, cartel, or cooperative group will conserve more than the social planner. He also describes the deadweight loss created by a monopolist compared to the first-best outcome and the factors that increase or decrease this net loss to society. Manning and Uchida (2016) extend this framework and discuss the distributional impacts of sole-ownership in fisheries. Both of these researchers find the difference between the first-best level of harvest and the monopolist's optimal harvest is minimal when demand is highly elastic and stock dependant costs are low. Conversely, sole-ownership of a renewable resource leads to a significant deadweight loss when demand is inelastic and stock dependant costs are high.

Although sole-ownership and cooperative groups do not reach the level of efficiency of ITQ's, they do not incur any external management or enforcement costs.

A successful cooperative or cartel manages itself. For this reason, allowing monopolies, cartels, and cooperative groups to operate a fishery provides a potential efficiency increase when accounting for the cost of management. A sole owner of a marine resource has more control over a stock of fish and a greater incentive to maintain the habitat and growth of the stock. These factors suggest there are cases where monopolistic or cooperative management is better than ITQ's for managing fisheries.

If cooperative groups, cartels, and monopolists provide advantages over other management mechanisms used in fisheries, intermediate market power from oligopolies might also increase efficiencies when traditional management methods are ineffective or expensive. A small group of firms competing would not require external management or enforcement costs. A small enough group still has an incentive to maintain a healthy stock to ensure future profits. A small group of competing firms has less market power than a monopolist and will likely harvest more than a monopolist who over-conserves relative to the social planner. The following section will define the theoretical impacts of oligopoly power in a fishery compared to a monopolist and a social planner.

In the case of non-renewable resources, there is extensive research into the impacts monopolistic market power has on production. A monopolist acts as a conservationist, producing less than the first-best production path to maximize profits (Stiglitz 1976; Hotelling 1931). Manning and Uchida (2016) examine a dynamic fishery model and describe the market-wide impacts of monopoly ownership. They demonstrate that a monopolist restricts harvests and maintains a higher stock in a fishery compared to the first-best outcome and can arrive at a steady state which provides greater total welfare than the steady-state level of harvest reached by an open-access regime. Manning and Uchida identify that with market power, monopolistic ownership can serve as a second-best outcome. This second-best outcome is closest to the social planner's first-best result with highly elastic demand and costs that are highly responsive to stock levels.

In this paper, I extend the analysis performed by Manning and Uchida (2016) and define the steady-state outcomes for levels of intermediate market power. I compare the optimal harvesting path and the steady-state equilibrium of a Cournot oligopoly with a monopolist, social planner, and open-access regime. I find that there always exists a concentration of market power such that the Cournot oligopoly's steady-state is equal to the steady-state achieved by a social planner.

Theoretical Model

The theoretical model used here will closely relate to Manning and Uchida (2016) with a couple of notable additions.

A fishery exists with some stock of fish x_t. This stock evolves over time with a concave growth function equal to $F(x_t)$ such that $F''(x_t) < 0$. This growth function implies that when the stock is very small it grows quickly, and the rate of its growth slows as the stock gets larger. In graphic results below I use a logarithmic growth function which satisfies these properties. At time $t = 0$ there exists a stock $x_0 > 0$. Each period firms harvest from the stock of fish an amount h_t. In cases with multiple firms let H_t denote the total harvest in the fishery such that $H_t = \sum_{i=1}^{n} h_{i,t}$. This fishery serves consumers who have an inverse demand function given by $p(H_t)$ such that $p'(H_t) \leq 0$. Firms face costs given by $c(h_t, H_t, x_t)$. Costs are increasing in amount harvested $c_h(h_t, H_t, x_t) > 0$, increasing in total industry harvest $c_H(h_t, H_t, x_t) > 0$, and decreasing in the size of the stock $c_x(h_t, H_t, x_t) \leq 0$. Additionally, the marginal cost of harvest is decreasing in stock size $c_{xh}(h_t, H_t, x_t) \leq 0$, and increasing in amount harvested $c_{hh}(h_t, H_t, x_t) \geq 0$, and in the total industry harvest $c_{hH}(h_t, H_t, x_t) \geq 0$. This cost function captures the key factors present in common pool resources which exhibit the tragedy of the commons. Contemporaneous external costs are introduced with the increase in marginal harvesting cost from other firms activity and dynamic external costs are introduced as current harvests reduce future stock levels, increasing future costs. Finally, all agents discount future payoffs with a discount rate $\rho \in (0, 1)$. In this system, an open-access fishery with no management results in the degraded steady state level of stock and harvest where $p(H_t)H_t - c(H_t, H_t, x_t) = 0$ and $F(x_t) = H_t$. This open access steady state will be identified as e_{oa} in a number of figures below.

Throughout this analysis, I use several different notations to represent specific variables and derivatives of functions. Dot notation, a single dot above a function name, represents the first derivative of a function with respect to time. Apostrophes represent the first derivative of a function with a single variable, and functions with subscripts represent the derivative of a function with respect to the variable indicated in each subscript. For specific points, I use the subscripts *oa*, *sp*, *m*, and *c* to indicate open-access, social planner, monopolist, and Cournot competition, respectively.

To introduce the method of solving for the optimal strategies and steady-state values in this system, I begin by replicating the results for a monopolist and a social planner originally presented by Manning and Uchida (2016).

The Social Planner and the Monopolist

A social planner operates the fishery to maximize the present value of the resource, with a discount factor ρ. The present value of the resource is the difference between the marginal cost of harvesting c_h and the market price p. The social planner harvests h_t to maximize this difference over time subject to to the constraint on the growth of the stock over time, $F(x_t) - h_t$. This gives the following integral:

$$\underset{h_t}{max} \int_0^\infty \left(\int_0^{h_t} (p(k) - c_h(k, k, x_t))dk \right) e^{-\rho t} dt \quad s.t.\ \dot{x_t} = F(x_t) - h_t \tag{1}$$

Using k as the variable of integration and assuming an initial stock level of $x(0) = x_0 > 0$, we can solve the optimal harvesting path of the social planner using the current value Hamiltonian where λ_t as the co-state variable:

$$\mathbf{H} = \int_0^{h_t} (p(k) - c_h(k, k, x_t))\, dk + \lambda_t (F(x_t) - h_t) \tag{2}$$

The maximization principle is found by taking the derivative of the Hamiltonian with respect to h_t:

$$\lambda_t = p(h_t) - c_h(h_t, x_t),\ \forall t \tag{3}$$

In this case λ_t is equal to the marginal resource rent. It captures the intertemporal opportunity cost of harvesting today.

The state and co-state equations for this system are:

$$\dot{x_t} = F(x_t) - h_t \tag{4}$$

$$\dot{\lambda_t} - \rho\lambda_t = -(-c_x(h_t, h_t, x_t) + \lambda_t F'(x_t)) \tag{5}$$

Solving this system of equations results in the social planners optimal harvesting path for any initial stock x_0, ignoring time subscripts for simplicity:

$$\dot{h_{sp}} = \frac{(p(h) - c_h(h, h, x))(\rho - F'(x)) + c_x(h, h, x) + c_{hx}(h, h, x)(F(x) - h)}{p'(h) - c_{hh}(h, h, x)} = 0 \tag{6}$$

The optimal harvesting path of the social planner is to harvest such that $\dot{h_t} = 0$. From this result, we cannot say if h_{sp} is increasing or decreasing over time. It will depend on the initial stock level x_0. The denominator is strictly negative as $p'(x_t) \leq 0$ and $c_{hh}(h_t, h_t, x_t) \geq 0$. The social planner's decision to change the amount harvested will be opposite the sign of the numerator. If the initial stock is low, harvests will be low and slowly increase over time as the stock rebuilds and approaches the steady-state from below. If the initial stock is sufficiently high, harvests will be high and decrease over time, approaching the steady-state from above. A social planner will follow this optimal strategy until a steady state is reached where $\dot{h_t} = 0$ and $\dot{x} = 0$. It follows that the steady-state level of harvesting which maximizes total social welfare occurs when:

$$(p(h_t) - c_h(h_t, x_t))(\rho - F'(x_t)) + c_x(h_t, h_t, x_t) = 0 \tag{7}$$

Figure 1 presents this result in the stock/harvest space, visualizing how a social planner's optimal level of harvest, $\dot{H}_{sp} = 0$, evolves. It also shows the steady-state level of stock and harvests e_{sp}, in comparison to the open-access steady-state denoted by e_{oa}.

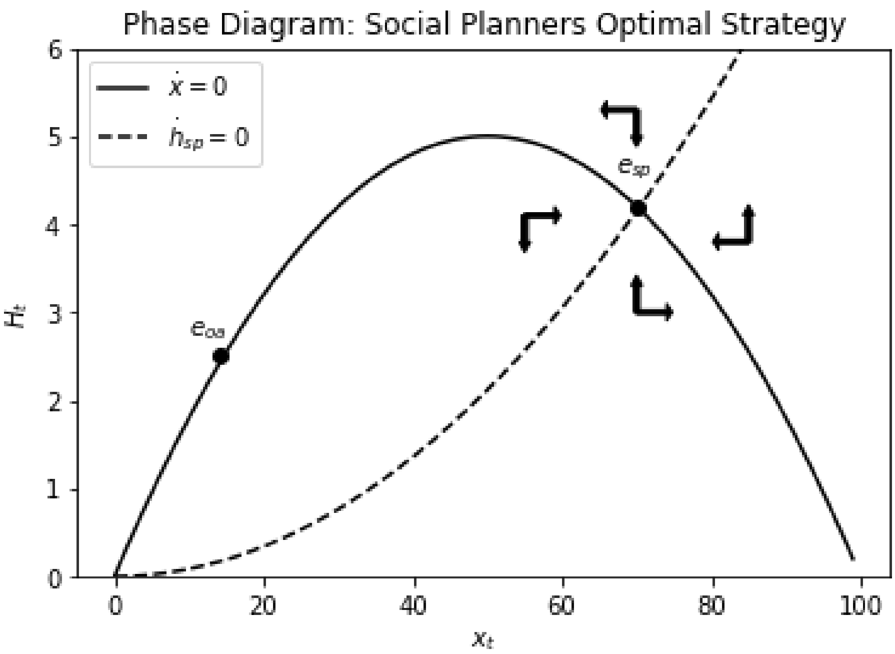

Figure 1. Phase plane of social planners optimal harvesting path. e_{sp} shows the social planners stable steady state.

This plot describes the optimal harvesting strategy of a social planner for any stock x_t that maximizes resource value. The stable steady-state, point e_{sp}, is reached for any starting stock value $x_0 > 0$. There is an additional steady-state at the point (0,0) when there are no fish and no harvest. This (0,0) steady-state is trivial and is ignored for the remainder of this analysis.

Unlike the social planner, a monopolist's goal is to maximize the present value of total profits. Current profits are revenue minus cost, $p(h_t)h_t - c(h_t, h_t, x_t)$. Maximizing profit for all of time subject to the stock growth constraint, the monopolist's optimal harvesting path is the solution to the following integral:

$$\underset{h_t}{max} \int_0^\infty (p(h_t)h_t - c(h_t, h_t, x_t))e^{-\rho t} dt \quad s.t. \; \dot{x}_t = F(x_t) - h_t \tag{8}$$

Following the same steps as above we can write the current value Hamiltonian equation:

$$\mathbf{H} = p(h_t)h_t - c(h_t, x_t) + \lambda_t(F(x_t) - h_t) \tag{9}$$

The maximization principle for the monopolist is defined by:

$$\lambda_t = p'(h_t)h_t + p(h_t) - c_h(h_t, x_t), \; \forall t, \tag{10}$$

It is important to note that λ_t no longer represents the resource rent as in the social planner's case. It is now equal to the resource rent plus the marginal revenue a monopolist earns.

The state and co-state equations for this system are:

$$\dot{x_t} = F(x_t) - h_t \tag{11}$$

$$\dot{\lambda_t} - \rho\lambda_t = -(-c_x(h_t, x_t) + \lambda_t F'(x_t)) \tag{12}$$

Combining these two equations with the maximization principle, the monopolists optimal rate of harvest over time, removing time subscripts for simplicity, is:

$$\dot{h_m} = \frac{(p'(h)h + p(h) - c_h(h, h, x))(\rho - F'(x)) + c_x(h, h, x) + c_{x,h}(h, h, x)(F(x) - h)}{p''(h)h + 2p'(h) - c_{hh}(h, h, x)} \tag{13}$$

The monopolist's optimal strategy is given by $\dot{h_m} = 0$. In steady state $\dot{h_m} = 0$ and $\dot{x_t} = 0$. It follows that the steady-state level of harvest for a monopolist in this fishery occurs when:

$$(p'(h_t)h_t + p(h_t) - c_h(h_t, h_t, x_t))(\rho - F'(x_t)) + c_x(h_t, h_t, x_t) = 0 \tag{14}$$

Figure 2 plots of the monopolist's optimal harvesting path in the harvest/stock space. The steady state level of harvest and stock is denoted by e_m.

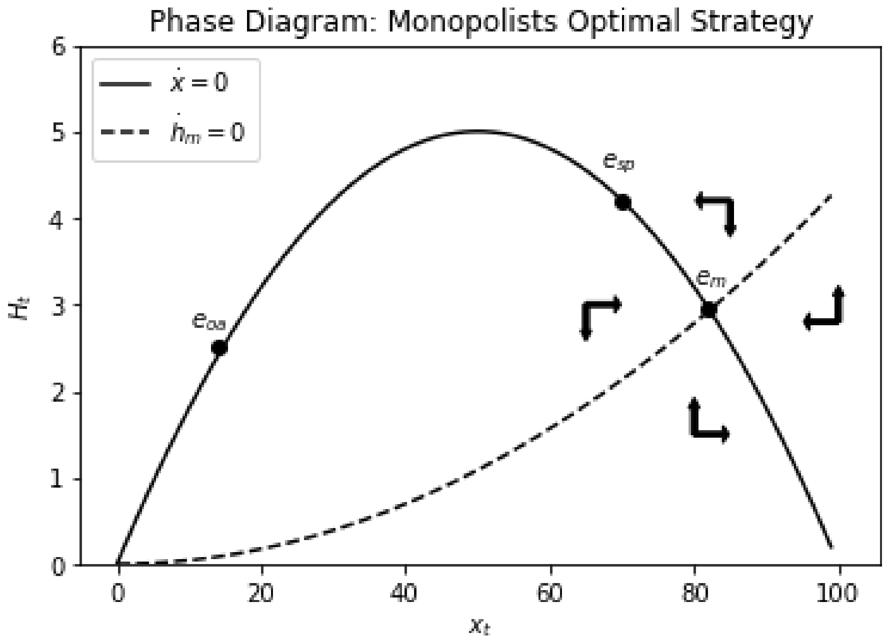

Figure 2. Phase plane of the monopolists optimal harvesting path. e_m shows the monopolists stable steady state.

Comparing Figure 2 and Figure 1, it is clear that a monopolist conserves a higher stock level than the social planner. For any stock size x_t, a monopolist will harvest fewer than the social planner. The symbolic solutions to the optimal harvesting strategy for each market structure reflect these facts. This result matches the central findings of Manning and Uchida (2016) and aligns with economic intuition. A social planner has to balance the benefits of high harvests for consumers and high stocks for firms. All else equal, a monopolist prefers higher prices and can increase profits by harvesting fewer fish than the social planner, further reducing costs by allowing the stock to increase in size.

A monopoly is an extreme market structure. A fishery does not need to be operated by a single harvester or left as open access. There are intermediate levels of market power that may provide useful outcomes in markets for renewable resources.

The Cournot Duopoly

A Cournot duopoly exists in a market with two profit-maximizing firms that produce homogeneous products, have market power, compete in quantities, and act as strategic rational agents. Both firms have perfect information and react to competitor's decisions without delay. To model this type of competition, with multiple firms, it will be valuable to reintroduce the notation $H_t = \sum_{j=1}^{N} h_{j,t}$. In this case $N = 2$.

The cost curve for each firm is represented by $c^i(h_{i,t}, H_t, x_t)$. It is important to note that each firm does not need to have an identical cost function. One firm may be more efficient at harvesting due to technological advantage, geographic location, or specialized knowledge. Both firms do serve identical consumers with a shared demand curve, $p(H_t)$.

In a Cournot duopoly, each firm acts as a profit maximizer and will maximize profits given its competitor's selected harvest. When firms have perfect information, each firm is aware of the best response function of its competitor. Both firms choose a level of harvest which maximizes the present value of profits, given that their competitor harvests according to their best response function.

Firm 1's best response function is given by solving the profit maximization problem for all possible values of firm 2's harvest, where $H_t = h_{1,t} + h_{2,t}$:

$$\underset{h_t^1}{max} \int_0^\infty (p(H_t)h_{1,t} - c^1(h_{1,t}, H_t, x_t))e^{-\rho t}dt \quad s.t.\ \dot{x}_t = F(x_t) - H_t \tag{15}$$

Following the same steps as for the monopolist, the current valued Hamiltonian equation for firm 1 is:

$$\mathbf{H} = p(H_t)h_{1,t} - c^1(h_{1,t}, H_t, x_t) + \lambda_t(F(x_t) - H_t) \tag{16}$$

The maximization principle for firm 1 is defined by:

$$\lambda_t = p'(H_t)h_{1,t} + p(H_t) - c_h^1(h_{1,t}, H_t, x_t),\ \forall t \tag{17}$$

The state and co-state equations for firm 1 are:

$$\dot{x}_t = F(x_t) - H_t \tag{18}$$

$$\dot{\lambda}_t - \rho\lambda_t = -(-c_x^1(h_{1,t}, H_t, x_t) + \lambda_t F'(x_t)) \tag{19}$$

Combining these two equations with the maximization principle, firm 1's best response function over time, removing time subscripts for simplicity, is given by:

$$\dot{h_1} = \frac{(p'(H)h_1 + p(H) - c^1_{h_1}(h_1,H,x))(\rho - F'(x)) + c^1_x(h_1,H,x) + c^1_{x,h_1}(h_1,H,x)(F(x)-H)}{p''(H)h_1 + 2p'(H) - c^1_{h_1h_1}(h_1,H,x)} = 0 \tag{20}$$

Similarly firm, 2's best response function is:

$$\dot{h_2} = \frac{(p'(H)h_2 + p(H) - c^2_{h_2}(h_2,H,x))(\rho - F'(x)) + c^2_x(h_2,H,x) + c^2_{x,h_2}(h_2,H,x)(F(x)-H)}{p''(H)h_2 + 2p'(H) - c^2_{h_2h_2}(h_2,H,x)} = 0 \tag{21}$$

Having perfect information, firm 1 observes firm 2's best response function and selects a level of harvest which maximizes profits based on expectations of firm 2's best response. Firm 2 does the same; observing firm 1's best response function, firm 2 selects a level of harvest which maximizes profits based on expectations of firm 1's best response.

With this information, both firms consider H_t to be a function of only their harvest. From firms 1's point of view the total harvest is equal to firm 1's harvest plus firm 2's best response, $H_t = H(h_1) = h_1 + h_2(h_1)$. Firm 1 now has the optimal harvesting path given by the set of points that satisfy:

$$\frac{(p'(H(h_1))h_1 + p(H(h_1)) - c^1_h(h_1,H(h_1),x))(\rho - F'(x)) + c^1_x(h_1,H(h_1),x) + c^1_{x,h}(h_1,H(h_1),x)(F(x)-H(h_1))}{p''(H(h_1))h_1 + 2p'(H(h_1)) - c^1_{hh}(h_1,H(h_1),x)}$$
$$= 0 \tag{22}$$

Similarly firm 2's optimal harvesting path, given firm 1's best response, is:

$$\frac{(p'(H(h_2))h_2 + p(H(h_2)) - c^2_h(h_2,H(h_2),x))(\rho - F'(x)) + c^2_x(h_2,H(h_2),x) + c^2_{x,h}(h_2,H(h_2),x)(F(x)-H(h_2))}{p''(H(h_2))h_2 + 2p'(H(h_2)) - c^2_{hh}(h_2,H(h_2),x)}$$
$$= 0 \tag{23}$$

The optimal harvesting path for the entire fishery is defined by the set of points that satisfy $\dot{h_1} = \dot{h_2} = 0$. A steady state equilibrium will be reached in this fishery when $\dot{h_1} = \dot{h_2} = \dot{x} = 0$.

To simplify this analysis, I repeat the same steps for the special case of the symmetric duopoly. In the symmetric duopoly, both firms have identical cost functions.

The best response function for each firm is unchanged from the asymmetric case. The best response function for either firm, removing time subscripts for simplicity, is given by:

$$\dot{h}_i = \frac{p'(H)h_i + p(H) - c_h(h_i, H, x))(\rho - F'(x)) + c_x(h_i, H, x) + c_{x,h}(h_i, H, x)(F(x) - H)}{p''(H)h_i + 2p'(H) - c_{hh}(h_i, H, x)} = 0 \tag{24}$$

With perfect information, each firm knows the best response function of their competitor and considers the total harvest to be a function of only their harvest, given that their competitor will always harvest according to their best response function. Firms can calculate H_t as a function of their own harvest, $H_t = H(h_{i,t})$. Each firm selects a level of harvest that maximizes profit such that:

$$\frac{p'(H(h_i))h_i + p(H(h_i)) - c_h(h_i, H(h_i), x))(\rho - F'(x)) + c_x(h_i, H(h_i), x) + c_{x,h}(h_i, H(h_i), x)(F(x) - H(h_i))}{p''(H(h_i))h_i + 2p'(H(h_i)) - c_{hh}(h_i, H(h_i), x)}$$
$$= 0 \tag{25}$$

The fishery will be at a steady state equilibrium when $\dot{h} = \dot{x} = 0$. This is achieved when:

$$p'(H(h_i))h_i + p(H(h_i)) - c_h(h_i, H(h_i), x))(\rho - F'(x)) + c_x(h_i, H(h_i), x) = 0 \tag{26}$$

Given that the firms are symmetric and have equivalent response functions, it must be the case that $h_1 = h_2 = \frac{H}{2}$ on the optimal harvesting path.

Figure 3 plots the symmetric duopolists' optimal harvesting path in the stock/harvest space. With two firms in this fishery, the optimal harvesting path $\dot{H}_c = 0$ is the sum of both firms' harvests. The steady-state is denoted by e_c.

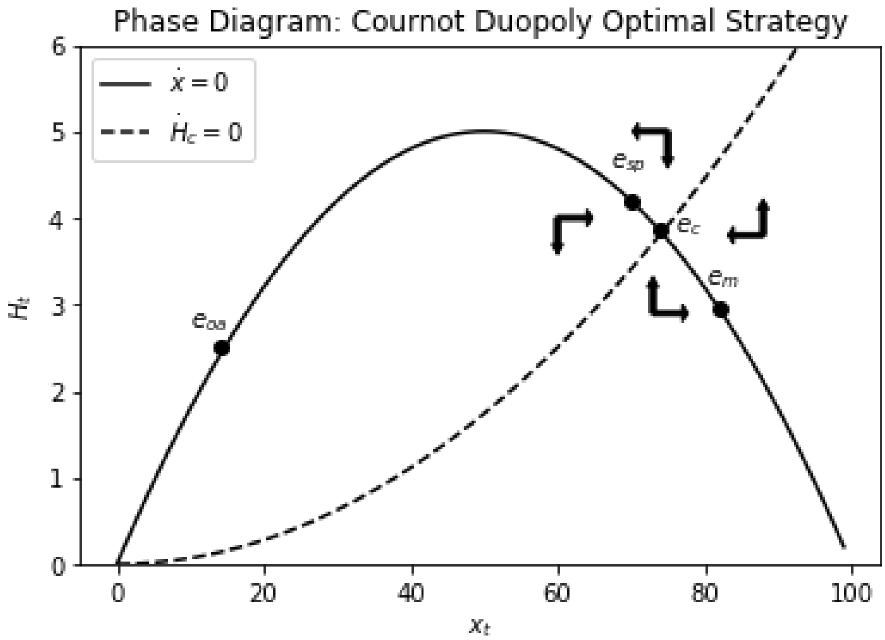

Figure 3. Phase plane of the symmetric duopoly's optimal harvesting path. e_c shows the stable steady state.

The important result here is the symmetric Cournot duopoly harvests more than a monopolist for any given stock level. The difference in total harvest between the monopoly and duopoly will depend on all of the parameters. The duopolist will never harvest less than a monopolist.

Symmetric N-Firm Cournot Oligopoly

Extending the above result to the more general case of Cournot competition among N symmetric firms, not allowing for entry or exit, H_t is now a function of each firm's harvest and the number of firms in the fishery such that $H_t = \sum_{j=1}^{N} h_{j,t}$. Similar to firms in the symmetric duopoly, each of the symmetric oligopolists' best response functions are equal to the following:

$$\frac{p'(H)h_i + p(H) - c_h(h_i, H, x))(\rho - F'(x)) + c_x(h_i, H, x) + c_{x,h}(h_i, H, x)(F(x) - H)}{p''(H)h_i + 2p'(H) - c_{hh}(h_i, H, x)} = 0 \tag{27}$$

All N firms share the above best response function and all firms harvest with the knowledge that each competitor will respond according to this best response function. The i^{th} firm selects a harvest with the knowledge that $H_t = H(h_{i,t}, N) = h_{i,t} + \sum_{j \neq i} h_{j,t}(h_{i,t})$. The optimal harvesting path for each firm, removing time and index subscripts for simplicity, is then given by the set of points which satisfy:

$$\frac{p'(H(h,N))h + p(H(h,N)) - c_h(h,H(h,N),x))(\rho - F'(x)) + c_x(h,H(h,N),x) + c_{x,h}(h,H(h,N),x)(F(x) - H(h,N))}{p''(H(h,N))h + 2p'(H(h,N)) - c_{hh}(h,H(h,N),x)}$$

$$= 0 \tag{28}$$

If all N symmetric firms follow the optimal harvesting path, we have $H_t = N \times h_i$. The steady state is given by the level of stock and harvest that satisfies $\dot{h_{i,t}} = \dot{H_t} = \dot{x_t} = 0 \quad \forall\ i \in [1, N]$. This occurs when:

$$p'(H(h,N))h + p(H(h,N)) - c_h(h,H(h,N),x))(\rho - F'(x)) + c_x(h,H(h,N),x) = 0 \tag{29}$$

Figure 4 shows the optimal harvesting path for various levels of oligopoly. As N increases, the optimal harvesting path moves from the monopoly solution at $N = 1$ towards the open access equilibrium.

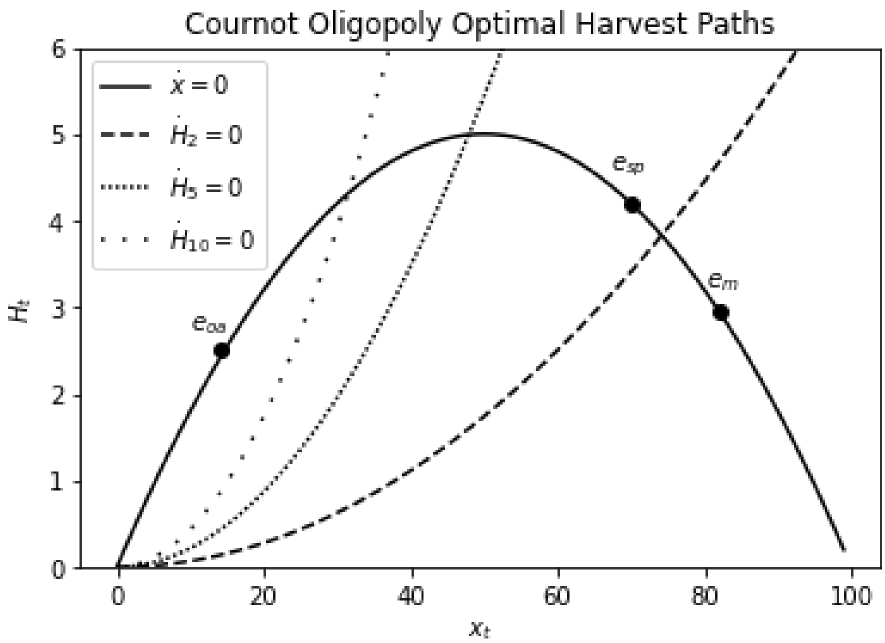

Figure 4. Phase plane of the 2, 5, and 10 firm oligopoly's optimal harvesting paths as H_2, H_5, and H_{10} respectively. e_{oa}, e_{sp}, and e_m show the steady states of open-access, a social planner, and a monopolist as before.

From figure 4, as the number of symmetric competing firms increases, the optimal strategy results in a higher harvest at any given stock level and a steady-state that maintains a lower stock level. For any $N > 1$, the steady-state level is to the left of the monopolist's steady-state. As $N \to \infty$ the N-firm oligopoly approaches the open-access steady state.

Steady State Results

The three steady states derived from this model of a fishery are given by:

Social Planner

$$(p(h_{sp}^{ss}) - c_h(h_{sp}^{ss}, h_{sp}^{ss}, x_{sp}^{ss}))(\rho - F'(x_{sp}^{ss})) + c_x(h_{sp}^{ss}, h_{sp}^{ss}, x_{sp}^{ss}) = 0 \tag{30}$$

Monopolist

$$(p'(h_m^{ss})h_m^{ss} + p(h_m^{ss}) - c_h(h_m^{ss}, h_m^{ss}, x_m^{ss}))(\rho - F'(x_m^{ss})) + c_x(h_m^{ss}, h_m^{ss}, x_m^{ss}) = 0 \tag{31}$$

N-Firm Symmetric Cournot Oligopoly

$$p'(H(h_c^{ss}, N))h_c^{ss} + p(H(h_c^{ss}, N)) - c_h(h_c^{ss}, H(h_c^{ss}, N), x_c^{ss}))(\rho - F'(x_c^{ss})) + c_x(h_c^{ss}, H(h_c^{ss}, N), x_c^{ss}) = 0 \tag{32}$$

Using the first two results above Manning and Uchida (2016) prove four propositions.

Proposition 1. The monopolist steady-state fish stock exceeds the social planner's steady-state stock.

Proposition 2. In general, it is unclear how the monopolist and social planner's steady-state harvests compare.

Proposition 3. If the open-access fishery begins at a fish stock level that is below the social planner's steady state, then the monopolist's steady-state fish stock exceeds the open-access steady-state stock size (x_{oa}).

Proposition 4. If the open-access fishery begins at a fish stock level that is below the social planner's steady state, then the per-period monopoly harvest could be less than or greater than the open-access steady-state harvest level.

These results are in line with my findings and allow for an extension when introducing Cournot competition. I suggest a fifth proposition:

Proposition 5. If the open-access fishery begins at a fish stock level below the social planner's steady-state, there exists some number of N firms such that a N-firm symmetric Cournot oligopoly will have an identical steady-state stock and harvest as the social planner.

Proof:

Intuitively, one can arrive at this result using the following three statements.

Combining proposition 1 with the fact that $F(x)$ is a strictly concave function, it must be true that $F'(x^{ss}_{sp}) > F'(x^{ss}_{m})$. At equilibrium, the social planner maintains a lower stock level than a monopolist. Given that $F(x)$ is strictly concave, a lower stock level corresponds to a higher growth rate.

With $N = 1$, it is clear that the monopolist and Cournot oligopoly solutions are identical, $F'(x^{ss}_{c}) = F'(x^{ss}_{m}) < F'(x^{ss}_{sp})$.

We know $H(h, N)$ is increasing in N, and as $N \to \infty$, the symmetric Cournot oligopoly approaches the degraded open access steady state, such that,
$F'(x^{ss}_{c}) = F'(x^{ss}_{oa}) > F'(x^{ss}_{sp})$.

Given that the open-access fishery begins at a fish stock level that is below the social planner's steady-state, $x^{ss}_{oa} < x^{ss}_{sp}$, and allowing for the number of firms to be a continuous variable. It must be the case that some number of firms, N^{*}, competing as a Cournot oligopoly will have a steady-state level of stock and harvest that is identical to the social planner.

Discussion

The results herein rely on several assumptions that are worth critiquing before discussing the applications of this research.

Critique of Key Assumptions

First, by comparing the results of a monopolist, social planner, and Cournot oligopoly, there is an assumption that all groups are infinitely lived and discount the future equally. An infinitely lived benevolent social planner acts in the best interest of society for eternity. Individual firms, maximizing lifetime profits, will likely discount the future more than a social planner. Additionally, in the long run, infinitely lived firms have no fixed costs. For firms owned by individuals with a limited lifespan, fixed costs play a vital role in decision-making. A fishery at a depleted stock level requires firms to earn small profits before reaching the profit-maximizing equilibrium. This path may not be profit-maximizing for firms with a short lifespan and high costs of entry.

In the case of Cournot competition, this model assumes all players will play the equilibrium strategy at all times, and all players have perfect information. Hongliang and Ma (2013) discuss the implications of rational competitors in a Cournot game with imperfect information and delayed responses in a market for renewable resources. Finding that the Cournot game can reach equilibrium, or, under some circumstances, the system can lead to chaos. If firms are not well informed or have a delayed response to competitors' actions, the system is less likely to reach the steady-state equilibrium described above. The results described by Hongliang and Ma (2013) suggest dangers in unregulated Cournot competition in markets for renewable resources.

The biology of a fish stock presented in this model is standard in the economic literature for fisheries; however, it is rather simplistic. In reality, biological systems are much more complex. Predator-prey relationships, stochastic variation in growth rates, and ecological change over time are all worth considering when discussing the dynamic impacts of harvesting strategies. With this in mind, the results from this model are general and can provide macro-level insights. To identify the exact costs and benefits of allowing for oligopoly market power in fisheries, collecting details on a case-by-case basis is necessary.

Applications

This research serves as an addition to the conclusions of Manning and Uchida (2016). The benefits of providing ownership rights in a fishery are clear. Allowing for sole ownership of a resource removes the external costs that lead to the tragedy of the commons; however, it introduces market power. In cases where the social planner's first-best outcome is not achievable due to lack of trust in management institutions, political instability, high costs of enforcement, or fish habitats extending across management boundaries. Sole or limited ownership is an option for management institutions.

In many developing nations, political instability, contentious ownership rights, and distrust in management institutions make it challenging for governments to manage resources effectively. Manning and Uchida (2016) suggest that in these cases, cooperative local ownership of resources serves as an effective second-best method to manage resources when the first-best option is not feasible. This model shows that the cooperation of a single group is not necessary. Limiting entry to a small number of individual firms can be preferable to a single cooperative group or monopolist and potentially equal to the first-best outcome.

In developed countries, where actively managed fisheries with ITQ's, equipment restrictions, and significant oversight, the results presented here may still be beneficial. For one, demersal (groundfish) species may live in regions that cross international borders. These regions are challenging to manage without communication between neighboring countries and significant investments from resource managers. My results suggest that each country can restrict entry and achieve the first-best outcome with little oversight or coordination across borders. Even within a single country, limited competition or monopoly ownership requires lower enforcement costs than current ITQ systems, potentially resulting in significant savings for management institutions and a net benefit to society.

Conclusion

By expanding on past research showing the theoretical impacts of monopoly ownership on fisheries, I model the effects of intermediate market power. I utilize the dynamic model of a fishery presented by Manning and Uchida (2016) and solve the profit-maximization problem of firms. Demonstrating that there are cases in which an oligopoly and a social planner have identical steady-state equilibria which maximize social welfare.

This research shows that introducing market power, allowing for coordination between firms, and limiting entry to fisheries has the potential to create welfare gains that can outperform current management mechanisms. Additionally, limited competition aligns firms' incentives with society's, reducing the need to invest in management and enforcement infrastructure.

The results apply to fisheries where traditional management techniques have failed, management institutions are untrustworthy, or when fish populations inhabit regions that cross national boundaries. Allowing firms to cooperate and create market power, either as a monopoly or an oligopoly, removes the need for oversight, quotas, or other restrictions.

References

Abbott, J., & Wilen, J. (2009). Regulation of fisheries bycatch with common-pool output quotas. *Journal of Environmental Economics and Management*, *57*. https://doi.org/10.1016/j.jeem.2008.04.003

Anderson, L. (1989). Enforcement issues in selecting fisheries management policy. *Marine Resource Economics*, *6*. https://doi.org/10.1086/mre.6.3.42871974

Arnason, R. (1990). Minimum information management in fisheries. *The Canadian Journal of Economics*, *23*. https://doi.org/10.2307/135652

Arnason, R. (2005). Property rights in fisheries: Iceland's experience with itqs. *Reviews in Fish Biology and Fisheries*, *15*. https://doi.org/10.1007/s11160-005-5139-6

Christy, F. (1973). Fisherman quotas: A tentative suggestion for domestic management. *Transportation Research Board*, 12–undefined.

Clark, C. (1990). *Mathematical bio-economics: The optimal management of renewable resources* (2nd ed., Vol. 10). John Wiley & Sons. https://doi.org/10.2307/134310

Costello, C., & Polasky, S. (2008). Optimal harvesting of stochastic spatial resources. *Journal of Environmental Economics and Management*, *56*, 1–18. https://doi.org/10.1016/J.JEEM.2008.03.001

FAO. (2012). *Cooperatives in small-scale fisheries: Enabling successes through community empowerment*. Food and Agriculture Organization of the United Nations.

Gordon, H. (1954). *The economic theory of a common-property resource: The fishery*. https://doi.org/10.1057/9780230523210_10

Grafton, Q. (1996). *Individual transferable quotas: Theory and practice*.

Hongliang, & Ma, J. T. (2013). Complexity and control of a cournot duopoly game in exploitation of a renewable resource with bounded rationality players. *WSEAS Transactions on Mathematics*, *12*, 670–680.

Hotelling, H. (1931). The economics of exhaustible resources. *Journal of Political Economy*, *39*. https://doi.org/10.1086/254195

Hoy, M., Livernois, J., McKenna, C., Rees, R., & Stengos, T. (2011). *Mathematics for economics* (3rd ed.). MIT Press.

King, B. (2009). *Sustaining alaska's fisheries: Fifty years of statehood.* Alaskan Department of Fish and Game.

Manning, D., & Uchida, H. (2016). Are two rents better than none? when monopolies correct ill-defined property rights. *Marine Resource Economics*, *31*. https://doi.org/10.1086/685101

Munro, G., & Scott, A. (1985). *The economics of fisheries management.* https://doi.org/10.1016/S1573-4439(85)80021-X

Scott, A. (1955). The fishery: The objectives of sole ownership. *Journal of Political Economy*, *63*. https://doi.org/10.1086/257653

Smith, V. (1968). Economics of production from natural resources. *The American Economic Review*, *58*, 409–431. http://www.jstor.org/stable/1813767

Somers, K., Pfeiffer, L., Miller, S., & Morrison, W. (2018). Using incentives to reduce bycatch and discarding: Results under the west coast catch share program. *Coastal Management*, *46*. https://doi.org/10.1080/08920753.2018.1522492

Stiglitz, J. (1976). Monopoly and the rate of extraction of exhaustible resources. *The American Economic Review*, *66*, 655–661. http://www.jstor.org/stable/1806704

Wilen, J. (2000). Renewable resource economists and policy: What differences have we made? *Journal of Environmental Economics and Management*, *39*. https://doi.org/10.1006/jeem.1999.1110