Emerging Issues in Fisheries Management: An Intersection of Institutional and Resource Economics

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Abstract

This dissertation investigates contemporary challenges and promising remedies regarding fishery management: aquaculture production, trans-boundary fish movements, and the transition from open access to rights-based management.

Aquaculture as a Backstop: Fisheries Management in the Presence of Aquaculture Production investigates aquaculture production in a context of capture fishery management. The study shows the impacts of aquaculture, as a backstop technology, on a capture fishery under optimal and open-access regimes. The study finds that aquaculture production serves as a backstop so long as the aquaculture production cost is smaller than the output price at the steady state. If the marginal user cost with a backstop is greater than without a backstop, aquaculture production contributes to conserving more wild stock compare to the case without aquaculture production.

Cooperative Management of Trans-boundary Fish Stocks: Implications for the Tropical Tuna Management in the Pacific Island Region investigates cooperative management of trans-boundary fish stocks. The trans-boundary migration of fish stocks creates spatial externalities, and hence, makes international cooperation beneficial. This study provides a model to examine the relationship between fish migrations and cooperation. The model focuses on non-seasonal fish migration and takes stock leakages from exclusive economic zones into consideration. The study finds that leakages of stocks to international waters reduce the surplus gained from cooperative management. For a given stock leakage level, the surplus gain from cooperation increases with an increase in the gap between the two countries' fish migration rates. In order for two countries to reach a cooperation agreement, the country with higher migration rates may make side-payments to the other.

Institutional Evolution in Fisheries Management: Scarcity and the Intensity of Governance investigates the evolution of fishery management institutions. The study develops a model to show the optimal transition from open access to rights-based management. The study suggests that regulated open access, such as catch quota, can play a role as an intermediary institution before management switches to more efficient but costly rights-based management. The study finds that when there is learning by managing, catch quota may be used as an intermediary institution along the path to an individual transferable quota regime.

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x_t: Capture fishery harvest at time t

a_t: Aquaculture harvest at time t

$P(w)$: Inverse demand function

S_t: Capture fishery resource stock at time t

$c(S_t)$: Unit cost of capture fishery harvest

b: Unit cost of aquaculture harvest

$F(S_t)$: Fish growth function

λ_t: Multiplier for the fishery resource constraint

ρ: Time discount rate

r: Fishery resource stock's intrinsic growth rate

K: Carrying capacity of a fishery resource stock

$\bar{c}$: Positive constant

Chapter 3

$S_{i,t}$: Resource stock in country i at time t

$F(S_{i,t})$: Fish growth function

$x_{i,t}$: Harvest in country i's waters at time t

ϕi: Parameter for the stock leakages to international waters

δ_i: Parameter for the stock leakages from country i to country j's waters

p: Fixed output price

$c(S_{i,t})$: Unit cost of harvest

S_0: Stock at time $t = 0$

x^{max}: Upper bound of harvest for each time period by a country

ρ: Time discount rate

λ_t: Multiplier for country α's fishery resource constraint

μt: Multiplier for country β's fishery resource constraint

θ: Positive constant

γ: Fishery resource stock's intrinsic growth rate

κ: Carrying capacity of a fishery resource stock

$R(S_j)$: Pseudo function for a country i given country j's stock

π: Net present benefits

π^I: Net present benefits under non-cooperative management

σ: Parameter for a bargaining power

$\Pi_{i,j}$: Representative distant water fishing vessel j's profit from its operation in country i's waters

$x_{i,j}$: Representative distant water fishing vessel j's harvest in country i's waters

$d_{i,j}$: Number of days that a representative distant water fishing vessel j's operates in country i's waters

η_i: License fee of a fishing day in country i

ν: A representative vessel's average daily harvest

Chapter 4

p: Fixed output price

$x_{i,t}$: Harvest by an individual i at time t

$c(S_t, q_i)$ Unit cost of harvest

S_t: Resource stock at time t

q_i: Individual catchability coefficient

θ: Positive constant

Q_t: Fishery's harvest quota at time t

$Q_{i,t}$: Individual i's' quota share under the individual transferabl quota regime at time t

m: Price of a quota share

C: Fixed governance cost

g: Marginal governance cost

$F(S_{i,t})$: Fish growth function

$\bar{x}$: Upper bound of harvest for a fishery for each time period

ρ: Time discount rate

I: Fixed governance cost associated with the individual transferable quota regime

δ: Positive constant

z: Number of years in some form of management

Π: Present net benefits under different institutional evolution scenarios

Chapter 1

Introduction

1.1 Description of the Problem

Fishery resources are, in essence, renewable. However, a lack of resource governance can result in fisheries collapsing. Fisheries have coped with the problem of overharvesting for centuries. At the onset of the industrial revolution, steam engines allowed fishermen to fish farther from shore to increase their catch. In the 1880s, problems of stock depletion resulting from overfishing were already recognizable in some fisheries (Finley, 2011). In the 20th century, ironically, two World Wars put a moratorium on commercial fishing in many parts of the oceans, through which fishery resources recovered to healthy levels. The latter half of the 20th century has seen advances in fishing and naval navigation technologies, which have led to a dramatic increase in global fishery production (Figure 1.1). The FAO reports that employment in the fisheries and fish farming sector has increased more than twice since the 1970s (United Nations Food and Agriculture Organization, a). Along with that dramatic increase came stock depletion. More than 50% of the fish stocks are fully exploited and 24% of the fish stocks are either overexploited or depleted (United Nations Food and Agriculture Organization, b). Livelihoods are dependent on incomes from fisheries resources and an understanding of environmental and economic conditions surrounding fisheries resources. Renewable resources, when left unmanaged, can be completely exhausted, and this has economic consequences.

Economists play important roles in forming fishery management policies. This is owing to the fact that economics provides tools and insights that are essential for the efficient management of fisheries resources. For example, economists are credited for the introduction of catch share programs. Catch share programs allocate shares of pre-determined quota set by a fishery manager to individuals or groups of individuals (National Oceanic and Atmospheric Administration). The most common type of catch share program is called the individual

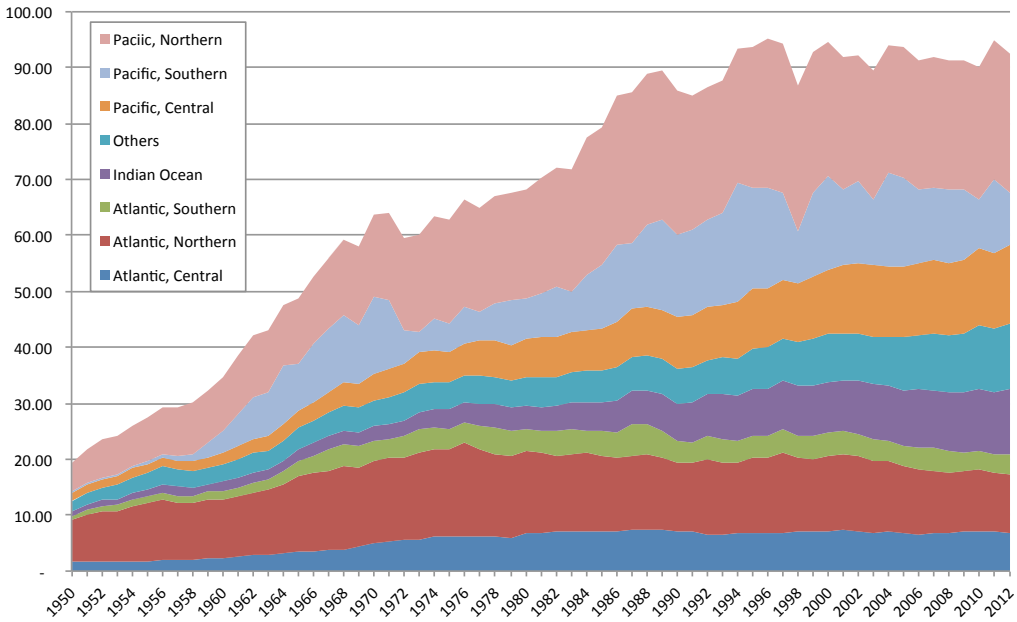


Figure 1.1: Global Capture Fishery Production (Metric Tonnes)

transferable quota, which allocates shares of a total quota to individual fishermen. Individual share holders are allowed to either fish for themselves or trade their shares with one another. Because catch share assigns tradable harvesting rights to individual fishermen, it corrects the incentives for fishermen to harvest until rent is dissipated. Another contribution made by economists is in the area of policy evaluation. For example, Costello et al. (2008) show that catch share could prevent fishery collapse.

Economists have also worked in collaboration with natural scientists to develop models to understand fishermen's behaviors under different environmental and management conditions. In particular, bioeconomic models that combine economic decision making and natural environmental and biological conditions play important roles in fisheries management around the world.

In this dissertation, I hope to contribute to this effort by developing new bioeconomic models. While fishery managers develop more elaborate and complex models, I focus my efforts on building simpler models. While the models presented in this dissertation are simple and may not be directly applicable to particular fisheries, they are useful in understanding some essential components of fishery management.

1.2 Frontier of Knowledge

Gordon (1954) formalized the problem of overharvesting by distinguishing the lack of prop-

erty rights over fishery resources as the source of the problem. If the ocean is monopolized, and if there is only one fisherman, he harvests up to the point where the marginal cost equals the marginal revenue. However, if there are many fishermen, they will overharvest to the point where rent is completely dissipated. This problem of rent dissipation is a static problem. The dynamic problem of overharvesting has to do with biology and fish population dynamics. The natural production of fish is governed by environmental and biological conditions, and can be expressed by a growth function. If we harvest more fish, there will be fewer fish left in the ocean to reproduce. This leads to stock depletion. Smith (1969) formalized the relationship between harvest and fish population dynamics that form the foundation for modern day fishery economics.

The realization of the overharvesting problem associated with open access fishing resulted in fisheries managers adopting policies to limit the harvest. One of the common management policies is a limited entry program, which limits the number of harvesters in the fishery. Another popular management policy is the designation of a fishing season, where a fishery is open for only a certain period of time of the year. In addition to this, fisheries have adopted catch quota, also known as total allowable catch, where a manager limits the number of harvests per season. However, these management policies resulted in an overcapitalization within the fisheries (Wilen, 1979).

A number of economists have pointed out the fact that none of these management policies directly address the source of problem, that is, ill-defined property rights. A management breakthrough occurred with the introduction of the individual transferable quota. By assigning harvesting rights to individual harvesters, individual transferable quota directly addresses the problem associated with ill-defined property rights. As I mentioned earlier, economists are credited with the development of the individual transferable quota program. Iceland and New Zealand especially embraced the individual transferable quotas by adopting it as national policy. While individual transferable quotas are found to be successful, economists are now pointing out problems associated with individual transferable quota programs.

Literature has pointed out two major pitfalls of the individual transferable quota program. First is the welfare effect of the individual transferable quota. Many fisheries that adopted the individual transferable quota program experienced fishery consolidation. Economically speaking, this is expected. Because fishermen are allowed to trade quotas for monetary compensation, fishermen with higher marginal costs are better of selling the quotas to those with lower marginal costs. This results in those with low marginal cost buying out quotas from those with high marginal cost. Theoretically speaking, this will lead to higher efficiency because only those with relatively low marginal cost will stay in the fishery. However, in reality, those with low marginal cost are often large corporations with more capital, and

they can potentially crowd the small-scale fishermen out of the industry. Many have pointed out this has negative impacts on the fishing community (Eythórsson, 2000). Such concerns have led economists to study the design of individual transferable quota programs in greater detail. Recent studies have focused on the initial allocation of quota shares in order to guide the fisheries' designs of individual transferable quota programs .

The second pitfall is that the assignment of rights (i.e. adoption of individual transferable quotas) may be delayed due to transaction costs (Libecap, 2007b, 2009). For instance, in order to implement an individual transferable quota program, a fishery must set up rules for quota allocation. If the program changes the welfare composition among the resource harvesters, it may take a long time to set up rules. This issue has been touched on by early essays on institutional change by Demsetz (1967) and Anderson and Hill (1975). Their argument is that institutional change, in our case, a switch to rights-based management, happens when the marginal benefit of assigning rights outweighs the marginal cost. Roumasset and Tarui (2013) have formalized this idea in their paper by presenting a model that links resource scarcity and the timing of institutional change. Chapter 4 of this dissertation extend this literature by focusing on the transition from open access to individual transferable quotas.

While these papers attempt to correct externalities associated with ill-defined property rights, there are other sources of externalities as well. One of the most challenging management issue derives from spatial externalities. Many fish species in the ocean move across the boundaries of multiple management jurisdictions. In order to efficiently manage such fisheries, one must take fish migration into management considerations. Classic literature on this topic has used a game theoretic approach to analyze international fish wars where multiple countries harvest shared, or common, stock (Levhari and Mirman, 1980; Munro, 1979). Recent literature has modeled the ocean as a patchy environment where multiple patches are inter-linked by fish migrations (Sanchirico and Wilen, 2001; Costello and Polasky, 2008). Chapter 3 of this dissertation extends this literature's effort to understand the spatial link between multiple fisheries.

While a relatively large number of papers and economists study the management of commercial fisheries, there are not many who study the aquaculture sector. As Figure (1.1) shows, commercial fishery production has stagnated in recent years and aquaculture is expected to fill the gap between the increasing demand for seafood and the stagnating supply from capture fisheries (Hannesson, 2003). This has implications for fisheries management. Because the aquaculture product is a very close, if not perfect, substitute to wild caught seafood, it is crucial to study the aquaculture sector in the context of fisheries management. Previous studies have shown a market interaction between capture fisheries and aquaculture (Anderson, 1985; Asche, 2008; Valderrama and Anderson, 2010). Chapter 2 of this disser-

tation builds on this literature by combining it with the framework used by Krulce et al. (1997), which applies a backstop model to study renewable resource.

1.3 Research Strategy

I develop dynamic bioeconomic models, using the work of Clark (1990) as a foundation to this dissertation. Dynamic optimization problems maximize present value of net benefits from resource harvesting given resource constraints. I adopt a logistic growth function to govern resource growth, which is the typical approach used in the consideration of fishery management. For each principle chapter, I develop a unique dynamic bioeconomic model to investigate the emerging issues faced by fisheries managers: aquaculture production, institutional evolution, and trans-boundary fish migration. I present steady state stocks and harvests and show the dynamic approach paths to the steady state through numerical illustration. Approach paths to the steady state are solved by following the time-elimination method in chapter 2 by following Mulligan and Sala-i Martin (1991) and the most rapid approach path in chapter 3 and 4 by following Spence and Starrett (1975).

1.4 Overview of the Principal Chapters

The main objective of my dissertation is to provide an analytical framework that helps fisheries managers determine an optimal management strategy. In particular, I examine three challenges and promising remedies regarding fishery management: aquaculture production, trans-boundary fish movements, and the transition from open access to rights-based management. The following offers a brief overview of the principle chapters of this dissertation.

Aquaculture as a Backstop: Explanation for the Increased Aquaculture Production in Global Seafood Supply

Aquaculture production has increased significantly since the 1980s while capture fishery production has stagnated since the 1990s. Meanwhile, global demand for seafood products has been increasing over time in conjunction with increasing world population. Aquaculture production is expected to grow to meet increasing demand. This trend is something that should not be ignored by a fishery manager. With the existence of aquaculture production, the optimal harvesting strategy for a capture fishery may be altered because wild caught and farmed fish are very close, if not perfect, substitutes. This chapter provides the framework to study aquaculture in the context of fisheries management. How does aquaculture production

alter the optimal harvesting paths of the capture fishery? Because capture fishery production and aquaculture production interact in the market, we need to examine them together. In this chapter, I treat aquaculture as a *backstop technology* to capture fishery production. The term *backstop technology* is traditionally used in the literature on optimal harvesting of non-renewable resources to define costly alternatives to non-renewable resources. Once the non-renewable resource is depleted, harvesting cost increases are sufficiently high so that costly alternatives become relatively affordable. The idea of a backstop technology is later adopted in the literature of the optimal pricing of water resources that places desalination as the backstop technology (Krulce et al., 1997). Building on Krulce et al. (1997), I show optimal harvesting in capture fisheries with aquaculture as a backstop under open access and optimal management regimes. In the case of fisheries, stock depletion due to overharvesting by open-access fisheries causes the price of wild fish to increase to the point where aquaculture technology becomes feasible.

Cooperative Management of Trans-boundary Fish Stocks: Implications for Tropical Tuna Management in the Pacific Island Region

Even when an individual country is able to manage their fisheries efficiently, we may fail to achieve optimal management on the global scale. This is particularly the case with trans-boundary fish stocks. The 1982 Convention on the Law of the Sea introduced exclusive economic zones as a convention, which granted coastal states fishery resource harvesting and management rights to the waters within 200 miles of their coastline. However, because some fish stocks, such as tunas, are highly migratory, and they move across exclusive economic zones, there may be a benefit from managing fishery activities through international cooperation. To investigate the benefits from the cooperative management of trans-boundary fish stocks, I develop a bioeconomic model that considers migration of fish stocks across exclusive economic zones and migrations from exclusive economic zones to international waters. The study shows links between fish migration parameters and cooperation benefits. The study also shows how the cooperation surplus may be shared between two countries.

Institutional Evolution in Fisheries Management: Scarcity and the Intensity of Governance

Economists have long argued that regulated open access management, such as catch quota and limited entry, does not successfully alleviate all the economic problems of fishery activities. That is, fishermen continue to input fishing effort until there is no economic rent even

when a manager limits harvest per season. However, many fisheries in the world continue to operate under regulated open access. This is most likely because of the large upfront cost associated with the implementation of rights-based management, such as individual transferable quota. In this chapter, I investigate the rationale behind this. I focus on the three common types of management regimes: open access, catch quota, and individual transferable quota. Under the catch quota regime, a manager sets a cap on total seasonal harvest by a fishery. Once the cap is reached, no more harvest is allowed. Under the individual transferable quota regime, each fisherman has to obtain quota shares, and his harvest is bounded by the amount of shares he owns. Fishermen are allowed to trade shares among themselves. While catch quota is relatively easy to be implemented, it does not change individual incentives to overharvest and fishermen continue to harvest until their rent is dissipated. On the other hand, individual transferable quota alters the incentives of individuals in a way that approximates first-best optimal. The down side to the individual transferable quota, however, is that it is more difficult to implement than the catch quota regime. This chapter extends the literature on institutional change in the resource management sector. The chapter investigates under which conditions an indirect transition from open access to individual transferable quota via catch quota may be an optimal institutional evolution path.

Chapter 2

Aquaculture as a Backstop: Fisheries Management in the Presence of Aquaculture Production

2.1 Introduction

In the last couple of decades, landings from capture fisheries have stagnated. Some researchers claim that the capture fisheries in the world will collapse by the year 2048 (Worm et al., 2006). While capture fishery production declines, aquaculture production has become the dominant force in overall production for some species such as shrimp and salmon. In 2009, aquaculture supplied more than 59% of the total salmon produced globally (FAO Fisheries and Aquaculture Department, a).

This study investigates the optimal management of commercial fishing activities given a competition against aquaculture production. How does the availability of aquaculture affect capture fisheries? How do the paths to the steady state differ under optimal and open access harvesting regimes? To answer such questions, I construct a a fishery manager's problem where I treat aquaculture as a backstop technology[1]. Then, I present numerical illustration to compare the steady state harvests from capture fishery and aquaculture, and compare the corresponding prices, and the stocks under optimal and open access harvesting regimes. The study shows that the existence of aquaculture alters the paths to the steady state. In reality, fishery operations fall somewhere between pure open access and optimal harvesting.

[1]In the study of finite resources, a backstop technology is something that is costly and which can be used once the resource is so depleted that its extraction cost becomes expensive. In this study, this traditional notion of a backstop becomes somewhat irrelevant. In the case of renewable resources, a backstop technology can be used from the outset. Though the term "backstop" is not exactly the right word in the case such technology is used, I use this terminology to follow convention.

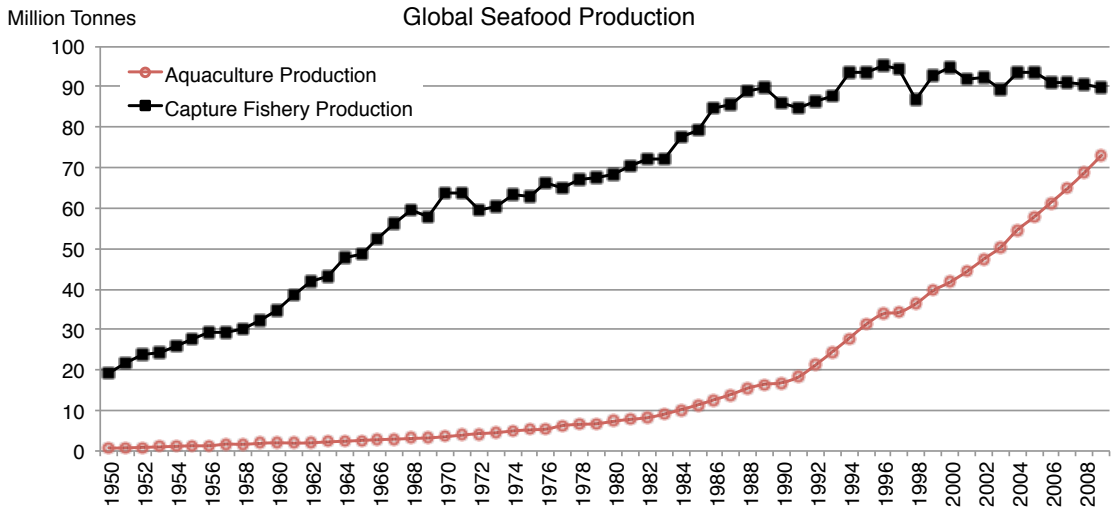
By analyzing the cases under two extreme regime types, pure open access and optimal, this study shows boundary cases.

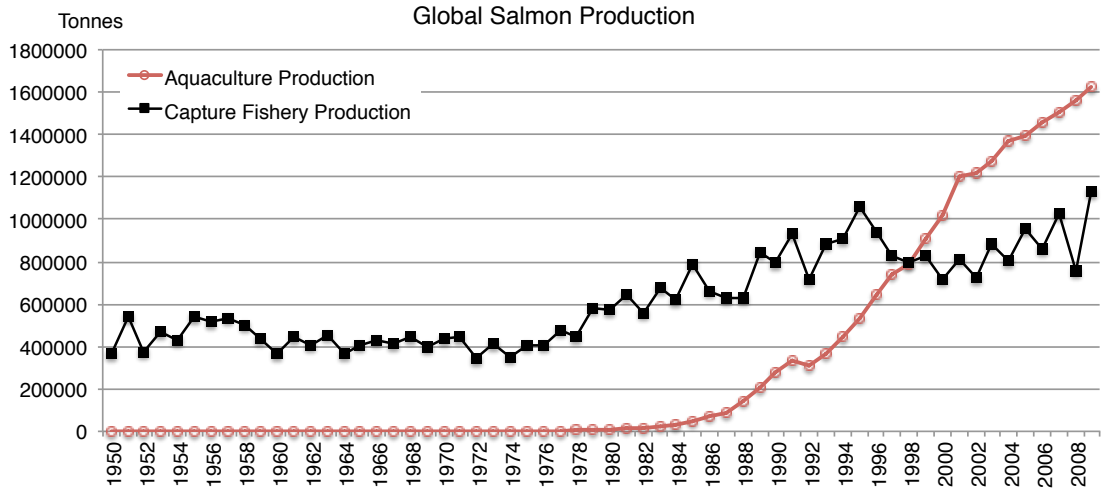
Previous studies in the fishery economics field focused on ways to correct externalities caused by ill-defined rights in open access capture fisheries. However, most of these studies do not take aquaculture production into consideration. Because aquaculture is a substitute technology that supplies the same market, it is crucial to understand how availability of aquaculture production affects fisheries harvest schedule. One cannot simply ignore the impacts of aquaculture production on catch fisheries when introducing governance, particularly when one tries to implement a policy to restrict the amount of harvests. This study contributes to the literature of fishery management by providing insights on how aquaculture production impacts capture fisheries and how those impacts may be different under the open access and optimal harvesting regimes.

While the fishery resource stock depletes and capture fishery production stagnates, recent technological development has led to an increased supply of seafood from aquaculture in the global markets. Global production of aquaculture has been increasing at the rate of 7.05% since the mid-1970s (Asche, 2008). Asche et al. (2008) claims that aquaculture is the only reason for the increased production of seafood. Figure 2.1 shows the global seafood production and salmon production since 1950. The figure shows the rapid increase in aquaculture production starting in the mid-1980s while capture fishery production remained flat. The trend is more prominent in the salmon market.

There are five key studies that analyze the interaction between aquaculture and wild-catch fisheries. Anderson (1985) shows that the entry of aquaculture contributes to the commercial fishery to achieve efficiency by lowering price and forcing capture fisheries to reduce their efforts. The study examines two types of market structures in the aquaculture industry, competitive aquaculturlists and a dominant-firm aquaculturlist. The study finds that entries of either types of aquaculture firm increases natural fish stocks, reduce prices, focuses capture fisheries to reduce their efforts, and increases total supply (Anderson, 1985).

Ye and Beddington (1996) extend Anderson (1985) by incorporating the substitutability between aquaculture fish and captured wild fish. They compare the cases when aquacultured fish have the same market value (i.e. perfect substitutes) and when cultured fish only have a substitute value to wild fish (i.e. imperfect substitutes). Ye and Beddington (1996) concludes that the existence of aquaculture lowers the price of wild fish, which leads the capture fishery efforts to shrink. This effect is more significant when aquacultured fish has the same market value as wild fish. When aquacultured fish have the same market value, price initially goes up then down. Supply from capture fishery harvests initially goes up and then down as aquaculture production increases. Over time, the supply from aquaculture production





Notes: Data from UN Food and Agriculture Organization FishStatJ.

Figure 2.1: Global Capture Fishery and Aquaculture Production

becomes greater than the one from capture fishery production (Ye and Beddington, 1996).

Both Anderson (1985) and Ye and Beddington (1996) use the partial equilibrium framework. Though their studies show the price interactions, they do not explain how aquaculture production comes into existence. Jiang (2010) attempts to answer the question of whether the wild stock decline has contributed to the increase in aquaculture production. The study uses the general equilibrium model to show that population growth has a downward effect on the wild stock while technological progress in aquaculture does the opposite. The study concludes that further development in aquaculture technology lowers the fish price and helps wild fish stocks recover (Jiang, 2010). The idea and the prediction of Jiang's study are very similar to the one to be offered in this study. Because Jiang's study only looks at the steady state, it is unclear how such steady state would be achieved. My study contributes to the literature by paying particular attention to the paths to the steady state.

Valderrama and Anderson (2010) empirically estimates the impacts of reduced salmon price due to an increase in supply of farmed salmon production on the Alaskan Sockeye salmon fishery. The study finds that the decrease in price leads to reduction in effort inputs in capture fisheries that operate under regulated open access.

While the above studies focus on the economic interaction between aquaculture and capture fisheries, Hannesson (2003) investigates the biological interaction by taking into account that aquacultured fish are fed with wild fish. The study concludes that aquaculture does not ease the tension in catch fisheries. What is more, the study indicates that aquaculture worsens the situation for the feed fish used for aquaculture production (Hannesson, 2003). For simplicity, my study does not factor in the interaction raised by Hannesson. However, in future research, the model can be extended to examine the case when aquaculture production uses wild fish as an input.

In this study, I treat aquacultured fish as a perfect substitute to captured wild fish. More precisely, this study views aquaculture as a backstop technology to capture fishery production. The idea of backstop comes from the analysis of non-renewable, exhaustible resource extraction. In his paper in 1973, Nordhaus analyzed the efficient energy prices and costs of energy resource, where the cost of resource is comprised of the extraction cost, marginal cost, and the royalty. The study points out that the cost of the backstop technology plays an important role in calculating royalty. In order to calculate the royalty, we need to know when the switch to the backstop technology will occur (Nordhaus et al., 1973).

Dasgupta and Heal (1974) show the framework for the optimal extraction of exhaustible resources, which is then re-evaluated by Heal (1976) for the case when non-exhaustible but costly backstop technology is available. The backstop technology becomes available at the time when the extraction cost of the exhaustible resource becomes as costly as the backstop

technology. The study shows that the existence of a backstop technology alters the optimal extraction path of the exhaustible resource presented by Dasgupta and Heal (1974) .

Krulce et al. (1997) extend the backstop model to study optimal pricing of groundwater. In the study, the authors examine the optimal price and extraction cost path of water from an underground aquifer when desalinated water could substitute as the resource gets scarce. In their study, desalinated water is assumed to be a costly backstop technology. Their study offers a framework to study optimal harvesting of the fishery resource with aquaculture as a backstop. As with the case of underground aquifer and desalinated water, fish growth is dictated by the natural environment. The overharvesting, hence, can lead to an increase in harvesting cost. A backstop would be introduced once the harvesting cost becomes as high as the production cost of a backstop technology.

One critical difference between the case of water and fishery is the management regime. While water is often managed by a central authority, such as board of water supply, fishery operates under sub-optimal management. Gordon (1954) first pointed out that unmanaged fisheries result in complete rent dissipation because of the lack of ownership rights. This also leads to over-harvesting of the fish, which leads to depletion of the stock. As the fishery stock depletion become severe, many fishery resource managers have taken actions to avoid rent-dissipation and overfishing [2].

To a large extent, economics of commercial fishery depends on the type of management regime in place. There has been an increase of rights-based management in the fishery sector. Theoretical papers suggest that a management practice such as individual transferable quota may function to restore efficiency in a fishery (Clark, 1990). The effectiveness of individual transferable quota is also supported by empirical papers. For instance, Costello et al. (2008) shows that an individual transferable quota system may prevent fishery collapse. In this study, I consider two extreme fishery management scenarios, pure open access and first-best optimal management, to examine optimal harvest and stock paths with aquaculture as a backstop.

[2]While open access fisheries still exist in many parts of the world, Homans and Wilen (1997) argue that the pure open access model does not represent the current real world situation in fishery management. In their regulated open access model, individual fishers may enter the industry until the rent is dissipated (i.e. open access entry), but the season length and harvest level is regulated. The most interesting implication from this model is that while regulated open access leads to more inefficient input use than in Gordon's model, the market reacts to the regulation of harvest levels with an increase in the market price, leading to increased revenue (Homans and Wilen, 1997).

2.2 Model

To show the optimal extraction of fish stocks, consider a fishery manager's problem with two harvesting technologies: capture fishery and aquaculture. The unit harvesting cost of capture fishery is dependent on stock in the ocean, S, and is denoted as $c(S)$, with $c'(S) < 0$ and $c''(S) > 0$ indicating a convex and declining cost function. The unit harvesting cost of aquaculture is a constant, denoted as b. For simplicity, we assume that captured fish and aquacultured fish are perfect substitutes, and the demand for the fish is denoted by $\int_0^{x_t+a_t} P(w)dw$. A manager's problem can be written as a dynamic constrained optimization problem

$$\begin{aligned} \max_{x_t, a_t} \quad & \int_{t=0}^{\infty} e^{-\rho t} \left\{ \int_0^{x_t+a_t} P(w)dw - c\left(S_t\right) x_t - ba_t \right\} dt \\ \text{subject to} \quad & \dot{S}_t = F(S_t) - x_t. \end{aligned} \tag{2.1}$$

The manager chooses the amount of capture fishery harvest, x_t, and aquaculture harvest, a_t. Growth of the wild fish stock S_t follows a stock growth function $F(S_t)$. The law of motion is the difference between the growth function and the capture fishery harvest. From (2.1), the Hamiltonian equation can be written as

$$\mathbb{H} = \int_0^{x_t+a_t} P(w)dw - c\left(S_t\right) x_t - \mathrm{ba}_t + \lambda_t \left\{F\left(S_t\right) - x_t\right\}$$

By applying the Maximum Principle, the following four conditions can be derived:

$$\dot{S}_t = \frac{\partial H}{\partial \lambda_t} = F\left(S_t\right) - x_t \tag{2.2}$$

$$\dot{\lambda}_t = \rho\lambda_t - \frac{\partial H}{\partial S_t} = \rho\lambda_t + c'\left(S_t\right) x_t - F'\left(S_t\right) \lambda_t \tag{2.3}$$

$$\frac{\partial H}{\partial x_t} = P\left(x_t + a_t\right) - c\left(S_t\right) - \lambda_t \leq 0 \text{ with equality when } x_t > 0 \tag{2.4}$$

$$\frac{\partial H}{\partial a_t} = P\left(x_t + a_t\right) - b \leq 0 \text{ with equality when } a_t > 0. \tag{2.5}$$

The next section will examine and compare the two harvesting regimes, optimal harvesting and open access harvesting, with and without aquaculture as a backstop.

2.2.1 Optimal Harvesting without Backstop

When aquaculture is not available, it is analogous to saying that $x_t > 0$ and $a_t = 0$. This indicates that the equality does not hold for the condition (2.5). The equality holds for the condition (2.4), and with the equality, the equation can be rearranged as,

$$\lambda_t = P(x_t) - c(S_t).$$

λ_t is a shadow price of the wild stock and can be expressed as a net price. This condition needs to hold at every period to satisfy the optimality condition. By taking a time derivative and rearranging the terms, we can derive

$$\dot{\lambda}_t = P'(x_t)\,\dot{x}_t - c'(S_t)\,\dot{S}_t. \tag{2.6}$$

From (2.2), we have

$$\dot{S} = F(S_t) - x_t \tag{2.7}$$

By substituting (2.7) in (2.6), and from (2.3), we can eliminate $\dot{\lambda}_t$ and get

$$\dot{x} = \frac{c'(S_t)F(S_t) + \{\rho - F'(S_t)\}\{P(x_t) - c(S_t)\}}{P'(x_t)}. \tag{2.8}$$

Equation (2.8) is an ordinary differential equation of time and stock. Together with equation (2.7), we have derived two equations of motions, $\dot{S}$ and $\dot{x}$. We use these two equations to solve the dynamic paths in the next section.

We can also rearrange equation (2.8) as,

$$p(x_t) = c(S_t) + \frac{\dot{x}_t P'(x_t) - c'(S_t)F(S_t)}{\rho - F'(S_t)} \tag{2.9}$$

This shows that the output price is a sum of unit harvest cost and marginal user cost. In the literature, the right hand side is also called as the marginal opportunity cost.

At the steady state, $\dot{x}_t = 0$ and $\dot{S}_t = 0$. From (2.7) and (2.8), the steady state capture fishery harvest can be expressed as 2.9.

$$x^* = F(S^*) \tag{2.10}$$

$$c'(S^*)F(S^*) = -\{\rho - F'(S^*)\}\{P(x^*) - c(S^*)\}.$$

By solving the above two equations for x^*, steady state harvest can be expressed as

$$x^* = \left[P(x^*) - c(S^*)\right]\frac{F'(S^*) - \rho}{c'(S^*)}.$$

By substituting (2.10), the steady state stock can be obtained by solving

$$F(S^*) = \left[P(F(S^*)) - c(S^*)\right]\frac{F'(S^*) - \rho}{c'(S^*)}$$

By rearranging this, the steady state net price can be expressed as

$$P(F(S^*)) - c(S^*) = \frac{c'(S^*)F(S^*)}{F'(S^*) - \rho} \tag{2.11}$$

This shows that the net price is equal to the marginal user cost.

2.2.2 Optimal Harvesting with Aquaculture as a Backstop

When a capture fishery follows optimal harvesting while aquaculture is available, an equality holds for (2.5) because $a_t > 0$, and it becomes

$$P(x_t + a_t) = b. \tag{2.12}$$

This indicates that that price is a constant as long as we have the positive aquaculture production. The constant price implies that the amount of harvest adjust so that the price stays constant. If the price is below the cost of a backstop, a backstop will not be used.

In the case of non-renewable resource with a renewable backstop, non-renewables (i.e. exhaustible resource) must be used up before it transition to the backstop Oren and Powell (1985). However, in the case of renewable resource with a backstop, we can continue to harvest from the resource even after the price becomes as high as the backstop cost. Hence, we have a positive harvest so that $x_t > 0$, which implies an equality to hold for (2.4). From this, we have

$$\lambda_t = P(x_t + a_t) - c(S_t). \tag{2.13}$$

From (2.12) and (2.13),

$$\lambda_t = b - c(S_t).$$

Because output price is equal to the backstop cost of production, it is no longer time variant.

By taking the time derivative, we have

$$\dot{\lambda}_t = -c'(S_t)\dot{S}_t.$$

Substitute this in (2.3) and solve for b. We have

$$b = c(S_t) + \frac{-\dot{\lambda}_t + c'(S_t)x_t}{F'(S_t) - \rho}.$$

The price is the sum of the extraction cost, $c(S_t)$, and marginal user cost, $\frac{-\dot{\lambda}+c'(S_t)x_t}{F'(S_t)-\rho}$. From (2.2), $x_t = F(S_t) - \dot{S}_t$. Plug this in and get

$$b - c(S^{*b}) = \frac{c'(S^{*b})F(S^{*b})}{F'(S^{*b}) - \rho}. \tag{2.14}$$

The left hand side is a relative cost difference between aquaculture production and capture fishery production. Also, because this equation has only one variable, S_t, therefore, we are able to find a constant stock level when aquaculture production exists.

Roumasset and Wada (2010) state that, in the transition to the steady state, the net benefit must be equal to the marginal opportunity cost. In order to find this condition, take a time derivative of equation (2.13),

$$\dot{\lambda}_t = P'(x_t + a_t)(\dot{x_t + a_t}) - c'(S_t)\dot{S}_t.$$

Together with equation (2.3), we are able to derive a condition

$$P(x_t + a_t) = c(S_t) + \frac{P'(x_t + a_t)(\dot{x_t + a_t}) - c'(S_t)F(S_t)}{\rho - F'(S_t)}. \tag{2.15}$$

We also know that if the price is below the backstop cost, the backstop will not be used so that $a_t = 0$. Hence, the equation (2.15) becomes (2.9), derived in the optimal case without a backstop.

2.2.3 Open Access Harvesting without a Backstop

When a capture fishery operates under an open access regime, its rent is completely dissipated. First, consider a case when there is no backstop so that $x_t > 0$ but $a_t = 0$. Complete rent dissipation means that

$$P(x^{OA}) = c(S^{OA}). \tag{2.16}$$

This shows that output price is equal to the unit cost of harvesting. By solving this for x, we are able to obtain the relationship between open access harvest, x_{OA} and stock, S_{OA}.

$$x^{OA} = P^{-1}[c(S^{OA})]. \tag{2.17}$$

At the steady state, $\dot{S}_t = 0$ and by (2.2),

$$x^{OA} = F(S^{OA}). \tag{2.18}$$

By solving (2.17) and (2.18), the steady state open access capture fishery harvest and stock can be derived. Also from (2.16) and (2.18), we have

$$p(F(S^{OA})) - c(S^{OA}) = 0 \tag{2.19}$$

This, again, indicates that the net price is zero. From (2.19), we are able to derive the steady state open access stock. The steady state open access harvest can consequently be derived by the equation (2.18).

2.2.4 Open Access Harvesting with Aquaculture as a Backstop

When aquaculture production cost is greater than the ouput price, then harvesting follows the open access regime case discussed in the previous section. When the output price is as high as the aquaculture cost of production, we have

$$P_t^{OAb} = b = c(S^{OAb}). \tag{2.20}$$

From the second equality, because the backstop cost is assumed to be exogenously determined, the stock level S^{oab*} can automatically be determined. From this, capture fishery harvest can also be determined by the condition

$$x^{OAb} = F(S^{OAb}).$$

From this and (2.20), we have

$$b - c(S^{OAb}) = 0 \tag{2.21}$$

Again, because backstop production cost is equivalent to the output price, this indicates that the net price is zero.

2.2.5 Comparison of the Four Cases

Let us summarize the steady state conditions derived for each of the cases examined.

Optimal without Backstop

$$P(F(S^*)) - c(S^*) = \frac{c'(S^*)F(S^*)}{F'(S^*) - \rho}$$

Optimal with Backstop

$$b - c(S^{*b}) = \frac{c'(S^{*b})F(S^{*b})}{F'(S^{*b}) - \rho}$$

Open Access without Backstop

$$P(F(S^{OA})) - c(S^{OA}) = 0$$

Open Access with Backstop

$$b - c(S^{OAb}) = 0$$

The difference between the optimal and open access regimes can be summarized as whether a net price is positive or zero. Under the optimal regime, the net price is positive and is equal to $\frac{c'(S)F(S)}{F'(S) - \rho}$. When aquaculture production exists, the output price is equal to the aquaculture production cost (i.e. $P(\cdot) = b$), and this is the defining difference between cases with and without aquaculture production.

At the steady state, the backstop exists when backstop production cost is smaller than the steady state price without a backstop. If the steady state price without a backstop is smaller than the backstop production cost, a backstop is not viable. This can be expressed as

$$\begin{aligned} P(x^{*b} + a) =& b < P(x^*) \\ P(F(S^{*b}) + a) <& P(F(S^*)) \end{aligned} \tag{2.22}$$

This reveals not only the relationship between the steady state price with and without a backstop, but also provides some information about the relative size of the steady state stocks with and without a backstop. To compare the relative size of the steady state stocks with and without a backstop, however, we need more information about the functional form of the inverse demand function. This will be discussed in the next section.

2.3 Numerical Illustration

This section applies the models presented in the previous section and illustrates how they can be used to explain how the availability and cost of aquaculture production affects capture fisheries. The objective of this illustration is to compare and analyze the steady state and approach paths to the capture fishery and aquaculture steady state harvests, and corresponding stock levels and prices. First, suppose the stock growth follows the logistic growth function,

$$F(S_t) = rS_t(1 - \frac{S_t}{K}),$$

where r represents the intrinsic growth rate and K represents the carrying capacity of the stock, S. Suppose the capture fishery unit harvesting cost function takes the form

$$c(S_t) = \frac{\bar{c}}{S_t},$$

where $\bar{c}$ is a positive constant. The unit cost function satisfies the conditions, $c'(S_t) < 0$ and $c''(S_t) > 0$. Hence, the capture fishery harvesting cost is convex shaped and declining as the stock level increases. Also suppose that the demand function takes the form

$$P(x_t + a_t) = \frac{1}{x_t + a_t}. \tag{2.23}$$

In the following sections, parameter values and constants are assigned as $\bar{c} = 3, \rho = 0.03, r = 0.5, K = 10$. We also suppose that aquaculture production cost is exogenously given as $b = 0.7$.

From equation (2.22), by applying the functional form for the inverse demand function as defined by equation (2.23), we have

$$\begin{aligned} \frac{1}{F(S^{*b}) + a} &< \frac{1}{F(S^*)} \\ F(S^{*b}) + a &> F(S^*) \\ \frac{(b - c(S^{*b}))(F'(S^{*b}) - \rho)}{c'(S^{*b})} &> \frac{(P(x^*) - c(S^*))(F'(S^*) - \rho)}{c'(S^*)}. \end{aligned} \tag{2.24}$$

From this condition, we can show that for the steady state stock with a backstop to be greater than the steady state stock without a backstop, the net price with a backstop must be greater than the net price without a backstop.

Table 2.1: Steady State

	Capture Harvest	Aquaculture Harvest	Stock	Price
Optimal	1.13	0	6.55	0.89
Optimal with Aquaculture	1.04	0.38	7.03	0.70
Open Access	1.11	0	3.33	0.90
Open Access with Aquaculture	1.22	0.20	4.29	0.70

2.3.1 Steady State

Table (2.1) shows the steady state capture fishery harvests, aquaculture harvests, wild stock levels, and prices for optimal and open access harvesting regimes with and without aquaculture production as a backstop. Comparing optimal and open access harvesting regimes without aquaculture production, the optimal regime yields higher capture fishery harvest than the open access regime. The differences in optimal and open access capture harvests and prices are small. Yet, the stock level is much greater for the optimal harvesting regime.

For both regimes, when aquaculture production exists, total harvest, defined by the sum of capture fishery and aquaculture harvests, is greater than when it does not exist. It is important to note that the production cost of aquaculture is exogenously given as $b = 0.7$, which must equal to the price at the steady state when aquaculture exists. This aquaculture production cost is the determinant of total harvest. In other words, there is an inverse relationship between the total harvest and aquaculture production cost.

Comparing optimal and open access regimes with aquaculture production, aquaculture harvest is greater for the optimal harvesting regime. For both regimes, steady state stock levels are greater when aquaculture is available. However, steady state capture fishery harvest is smaller when aquaculture is available under the optimal regime while it is greater under the open access regime.

2.3.2 Phase Diagram

To determine the optimal extraction paths to the steady states, we can use the time elimination method developed by Mulligan and Sala-i Martin (1991). Time elimination enables us to transform a system of equation of motions to a system of differential equations that are independent of time. By using this method, we are able to obtain the stable manifold in the phase diagram of stock and harvest.

In order to derive the paths, we first derive a relationship between wild stock and capture

fishery harvests by using two differential equations (2.7) and (2.8). By dividing (2.8) by (2.7),

$$\frac{\dot{x}}{\dot{S}} = \frac{\frac{dx}{dt}}{\frac{dS}{dt}} = \frac{dx}{dS} = -\frac{x[S]^2\left[\left(\frac{1}{x[S]} - \frac{\bar{c}}{S}\right)\left\{\frac{rS}{K} - r\left(1 - \frac{S}{k}\right) + \rho\right\} - \frac{\bar{c}r\left(1-\frac{S}{K}\right)}{S}\right]}{rS\left(1 - \frac{S}{K}\right) - x[S]}.$$

The equation represents the harvest, x, as an ordinary differential equation of the stock, S. Time variable, t, is eliminated in the equation. By solving this ordinary differential equation for x by using the initial value method, derive an optimal path, which represents a relationship between the wild stock and capture fishery harvest.

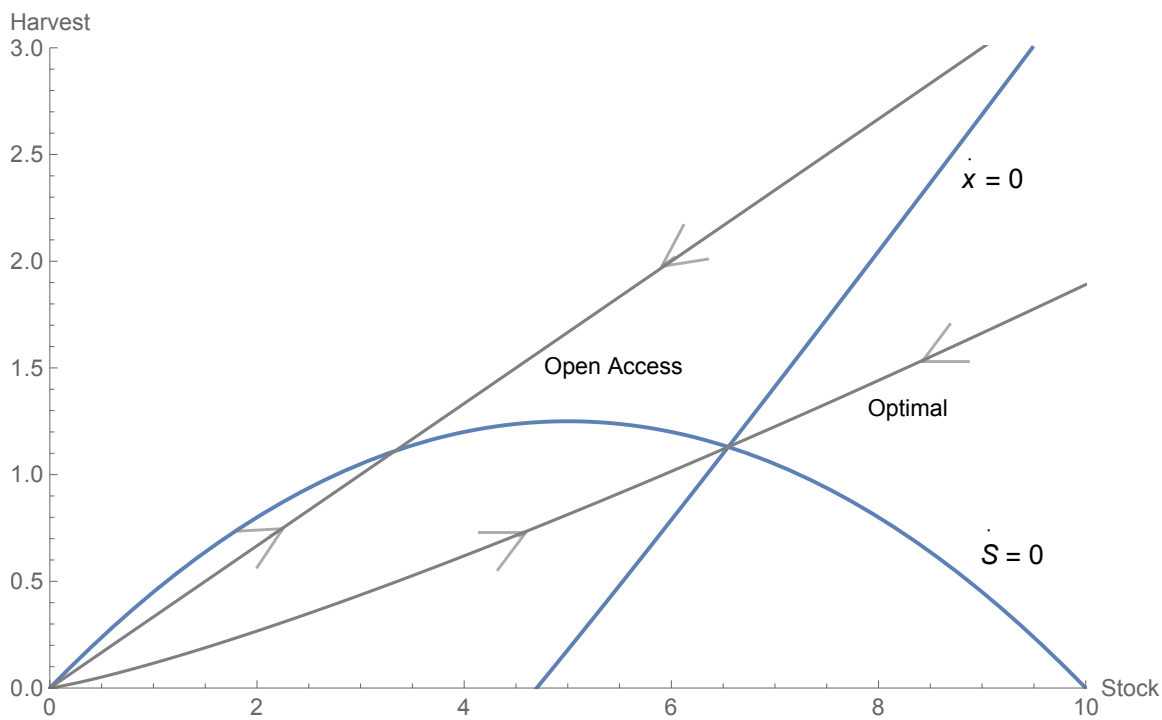


Figure 2.2: Phase Diagram

Figure 2.2 is the phase diagram that shows the relationship between the capture fishery harvest and the wild fish stock. Blue graphs depict the stock-harvest relationship derived from $\dot{S}_t = 0$ and $x_t = 0$. The stable arms for the optimal harvesting and open access regime are depicted by the gray lines. The arrows show the approach paths to the steady state. The time elimination method is used to find the trajectory for the optimal regime. For the open access regime, relationships between the capture fishery harvest and the wild stock are derived by the condition (2.16).

Under the optimal harvesting regime, initial stock depletion leads to the eventual increase in capture fishery harvest and stock while initial stock abundance leads to the eventual decrease in both stock and harvest. The steady state stock under the open access regime is

smaller than the maximum sustainable yield while it is greater than the maximum sustainable yield under the optimal regime. This comes from the assumptions on the functional forms of the cost and demand curves.

2.3.3 Transition Paths

Figure 2.3 shows the paths to the steady states over time for two initial conditions; when the stock is depleted at $S_0 = 1$ and when the stock is at carrying capacity at $S_0 = K$. The transition paths are calculated by using time elimination, and are depicted in the phase diagram (Figure 2.2). When the stock is depleted at the initial state and if aquaculture is available, you use aquaculture to supply all of the seafood. In the meantime, the wild stock grows back. Once the stock is sufficiently recovered, then you reduce the supply from aquaculture and let capture fishery supply the amount where $x = F(S)$. Price will be maintained at the same level when aquaculture is available. In this case, aquaculture is used extensively at the beginning. In other words, aquaculture production enables stock to grow back faster and to a higher level while the price is kept at a low level. This situation holds under both optimal and open access regimes.

On the other hand, when the stock is abundant at the initial state, the capture fishery continues to harvest to the point where the stock is so depleted that it becomes as costly as aquaculture. All of the supply is met by capture fishery production until then. Once it reaches that level, the capture fishery harvest drops down to the steady state harvest level, and aquaculture also produces at the steady state harvest level. The initially low price will increase up to the point where it is equal to the cost of aquaculture production. Aquaculture is capping the price at the aquaculture production cost.

Whether the stock is depleted or abundant, aquaculture production shortens the time it takes to reach the steady states. The difference is whether aquaculture production is used at the beginning or not.

There is a puzzle, however, that suggests a contradiction with our intuition. That is, with a backstop the future price is lowered compared to the case without a backstop. However, the transition path does not reflect this change in the future price of the output. There is a possibility that the transition to the backstop steady state may be altered. However, it is not clear whether the alternative transition path to the backstop steady state is an optimal path. The only information that we have about the transition path to the backstop steady state is that marginal benefit has to equal the marginal opportunity cost as described in Section 2.2.2. Because the time derivatives of stock and harvest are the same with and without a backstop, the stable arm depicted in the phase diagram is also the same in both cases. Yet,

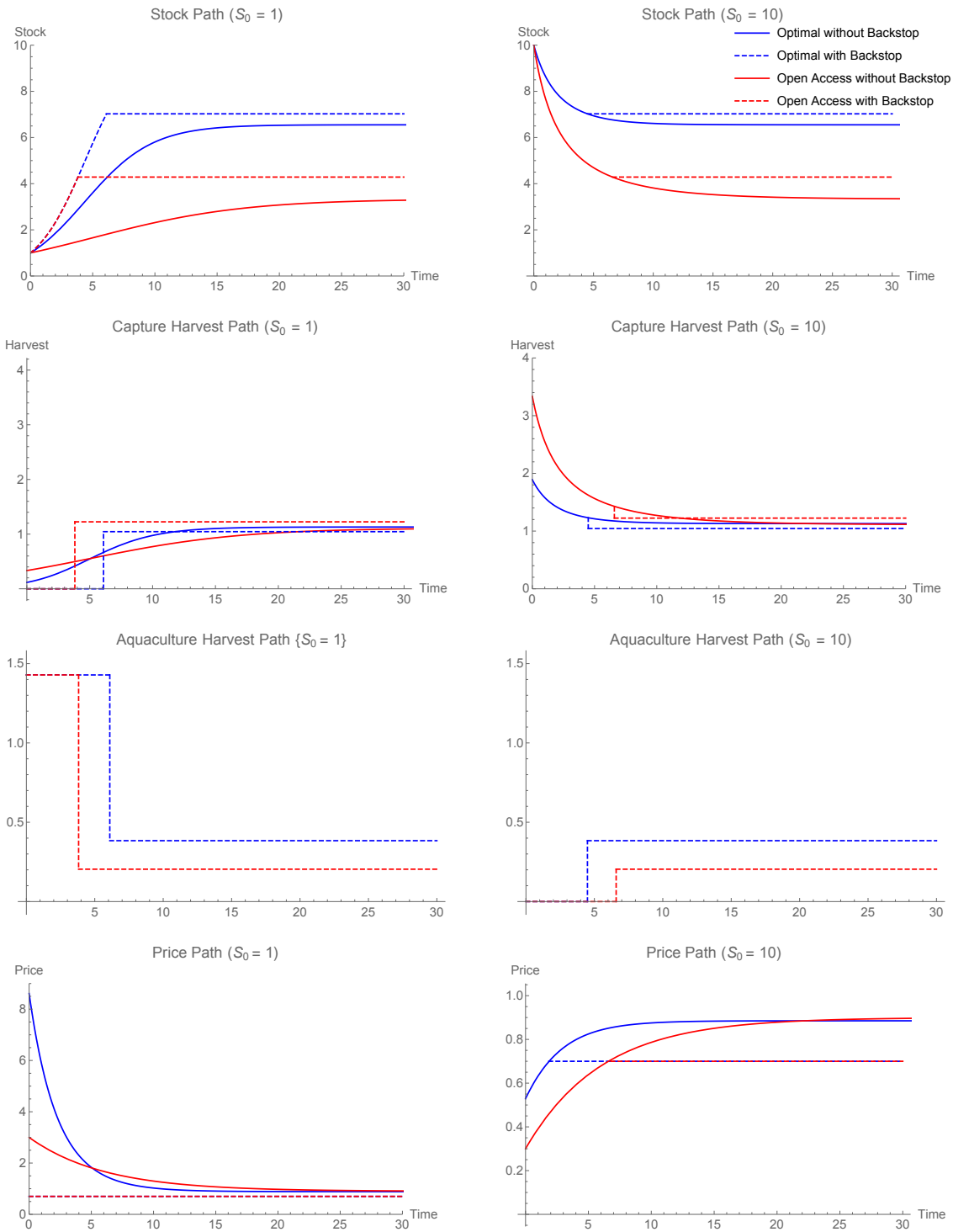


Figure 2.3: Transition Paths

the steady state stocks are different for each case. This needs further investigation in the future.

2.3.4 Relationship between Aquaculture Harvesting Cost and Stock

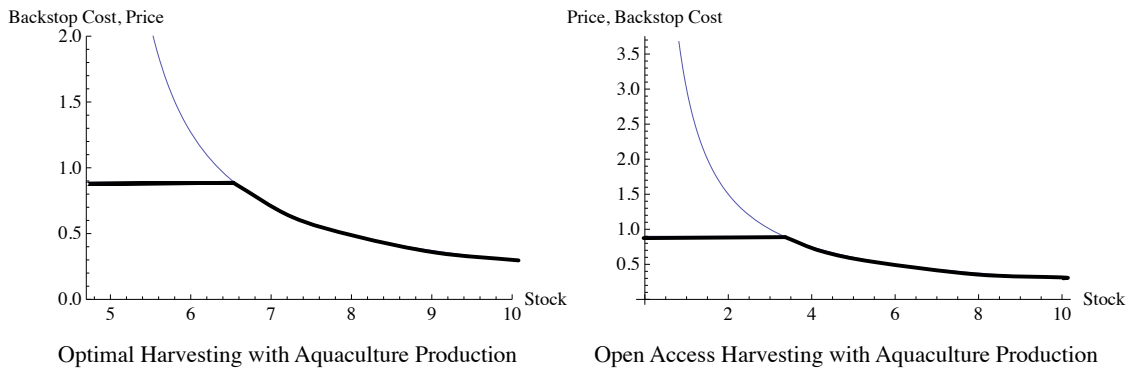


Figure 2.4: Relationship between Price, Backstop Cost, and Stock

Figure 2.4 shows the relationship between the aquaculture production cost and the stock. When aquaculture production cost is greater than the steady state capture fishery harvesting cost, then aquaculture technology will not be used. The graph for the optimal harvesting regime, which is the graph of equation (2.14), shows the relationship when it satisfies the condition $F'(S) < \rho$. The graph of the open access regime is the graph of equation (2.20). It is clear from both graphs that there are inverse relationships between the aquaculture production cost and wild stock for both regimes. In other words, when aquaculture production becomes cheap, it is possible to conserve more stock. Comparing the two regimes, at the same backstop cost, the optimal harvesting regime can conserve more stock than the open access regime.

2.4 Conclusion and Discussion

This study investigates the increased share of aquaculture production in the global seafood supply. Specifically, the study shows how the availability of aquaculture changes the steady state capture fishery harvest, wild stock, and price under two regimes: optimal and open access. Because capture fishery and aquaculture interact in the market, it is beneficial to study them together. To the author's knowledge, this study is the first to treat aquaculture as a backstop technology to capture fishery. The model follows the framework of the backstop technology applied to renewable resource management developed in Krulce et al. (1997), which examined optimal ground water management with desalinated water as a backstop.

Aquaculture production is only feasible if the backstop production cost is smaller than the steady state price without a backstop. We also show that with the assumption that the inverse demand function can be expressed as an inverse of harvests, the steady state stock with a backstop to be greater than the steady state stock without a backstop, the net price with a backstop must be greater than the net price without a backstop.

The study also shows the stock and price transition paths to the steady state. The numerical illustration shows that the rate and level of stock recovery are faster and higher when aquaculture is available. In the study, the availability of aquaculture production is determined by an exogenously given cost of aquaculture production. It is clear that the existence of aquaculture contributes to the steady state stock level being higher. Aquaculture shortens the time span to move to the steady state. In addition, the study shows an inverse relationship between the aquaculture production cost and the wild stock level. This indicates that the cheaper that aquaculture production becomes, the more stock in the ocean can be conserved.

Because the phase diagram suggests a common trajectory path until the stock reaches the backstop steady state, it poses a serious conundrum. Because a backstop reduces the future price of the resource, we would expect the trajectory to be altered when there is a backstop. Yet, because the stock and harvest equations of motions that dictate the transition paths are the same in both cases, the stable arm depicted in the phase diagram must hold for both cases. Future study should investigate this conundrum to complete the model of renewable resource management with a backstop.

The regime type is another component that determines the stock level. While both optimal and open access harvesting regimes exhibit inverse relationships between the aquaculture production cost and the stock level, the degree of conservation varies depending on the regime type. The numerical illustrations suggest that more stock is conserved under the optimal harvesting regime with the same aquaculture production cost. For instance, at the aquaculture production cost of 0.70, the wild stock level is 7.03 under the optimal harvesting regime while it is 4.29 under the open access regime. This is due to the shapes of the demand and cost curves. A convex shaped aquaculture production cost function suggests that the difference in marginal conservation will be higher when the aquaculture production cost is low enough.

This study assume that there is no biological interaction between aquaculture and capture fishery. While this may not be true for all cases, this holds for certain species. For example, most of the aquaculture production of salmon takes place in Norway and Chile. On the other hand, most of the capture production of salmon takes place in Alaska. In essence, there is no biological interaction between aquaculture production and capture fishery of salmon. In

other words, an increase in aquaculture production does not reduce the wild stock in Alaska. The only interaction between aquaculture and capture fishery happens in the market place. A backstop model would be a good starting point to analyze this kind of aquaculture and capture fishery interaction.

The study assumes that aquacultured fish have identical quality to captured wild fish. This may not be the case for some species. For instance, some captured fish may be preferred to aquacultured fish for their quality and lower chemical intake. Considering the case of salmon, aquaculture production has increased and currently supplies more than capture fishery. However, capture fishery production has not become zero. The assumption on perfect substitutability may be relaxed by changing the functional form of the demand function. In such cases, there will be two different prices for captured fish and aquacultured fish.

The study also assumes that the aquaculture production cost is constant and is not dependent on the wild fish stock. The study can be extended to the case when aquaculture production is dependent on the wild fish stock as it is suggested by other studies such as Hannesson (2003). In such a case, the model can be modified so that the aquaculture production cost function includes the wild stock as a variable.

In the real world, fishery operations exist somewhere in between optimal management and open access. Homans and Wilen (1997) argue that pure open access is no longer a common practice as more fisheries have some form of regulations, though they may not achieve the optimal outcome. Future research should investigate the impacts of aquaculture production when a fishery is under some form of imperfect management regime. Future research should also investigate the optimal policy and aquaculture production mix in preserving wild stock.

One policy implication from this study is that when the stock is depleted at the current stage, the resource managers can invest in aquaculture to drive its production cost lower. The results show that the lower the cost of aquaculture, the higher the steady state stock would be. Investment in aquaculture research and development, hence, has a positive effect in recovering wild fish stock. Alternatively, if managers can provide services and measures for disease control, they can alleviate the risks of operating aquaculture firms, and encourage higher entry to the aquaculture industry. The paths to the steady state shown by this study also provide insight to determining the timing of such investment. When stock is abundant, managers can predict at what stock and at what cost aquaculture should be introduced to preserve a desired level of wild stock.

The predictions of this study are such that availability of aquaculture production increases wild stock, decreases price, and increases total production. These predictions match with the ones presented by the previous study by Anderson (1985). Ye and Beddington (1996)

predicted that aquaculture production becomes greater than capture fishery production over time. In this study, however, the prediction is that aquaculture is either used in the starting period or as a backstop to stabilize the price and the wild fish stock. At the steady state, capture fishery produces more than aquaculture. This study also shows that the impacts on capture fishery depends on regime types and that the rate and level of stock recovery will be faster and higher when the stock is depleted at the initial stage. The study makes assumptions on substitutability, biological interconnection between captured and aquacultured fish, and the governance costs in the optimal harvesting regime, which may be relaxed in future research. The study clearly shows that availability of aquaculture alters the steady state harvests, stocks, prices, and the paths to the steady states, hence, offering insights to fishery managers for incorporating aquaculture production into their considerations for future policy implementation.

Chapter 3

Cooperative Management of Trans-boundary Fish Stocks: Implications for the Tropical Tuna Management in the Pacific Island Region

3.1 Introduction

The previous chapter examined the interaction between capture fishery and aquaculture production. Another emerging problem is the management of trans-boundary fish stocks. The past couple decades have seen an increase in international agreements to manage straddling and highly migratory fish stocks. Following the 1982 United Nations Convention on Law of the Sea and the establishment of Exclusive Economic Zones (EEZs), coastal states have actively sought to protect their sovereign rights over fish stocks within their 200-mile zones. The Law of the Sea Convention has also made coastal states responsible for managing their fishery resources. One of the challenges faced by coastal states in managing their fisheries resource is that fish do not observe man-made borders between EEZs and international waters. Many high-value fish, such as tuna, are highly migratory and, thus, it is essential for fisheries managers to take the resulting spatial externalities into their management considerations.

Economists have approached the problem of spatial externalities created by trans-boundary fish movements by using the game-theoretic framework. The first generation of literature examines harvesting behaviors of countries who share common stocks (Munro, 1979; Levhari

and Mirman, 1980). These studies, however, do not explicitly specify the migration patterns of the fish. More recent studies examine harvesting behavior when seasonal migration of fish cause spatial externalities (McKelvey et al., 2006; Hannesson, 2013). Another group of studies approaches spatial externalities by considering fishery grounds as a patchy environment, where patches with different environmental characteristics are interconnected through fish migrations (Sanchirico and Wilen, 1999). The patchy environment framework has been applied to examine the economic benefits of marine protected areas.

This study contributes to the literature of fisheries management with spatial externalities due to fish migration in three ways. First, the study aims to establish a model to analyze tropical tuna management by the Pacific island countries. Specifically, the model features non-seasonal fish migration and leakages of stocks from countries' EEZs to international waters. Skipjack tuna, which is the most sought after tuna species in the Western and Central Pacific, is known to congregate in locations with abundant feed (FAO Fisheries and Aquaculture Department, b). Therefore, non-seasonal migration plays a big role. As depicted in Figure 3.1, Pacific island countries' EEZs are surrounded by international waters. For this reason, it is imperative to take stock leakages from EEZs to international waters into consideration.

Second, the study provides an analytical framework to understand cooperative behavior by countries with migratory fish stocks. I present a dynamic fishery model for two countries with straddling and highly migratory fish stocks. Straddling stocks occur "both within the exclusive economic zone[s] and in an area beyond and adjacent to the zones (The United Nations, 1982)." The stocks migrate in and out of a country's waters, and part of the stocks could end up in a neighboring country's waters. I examine two management regimes to manage such stocks: a cooperative management regime and a non-cooperative management regime. Steady state harvests and stocks for each regime are derived numerically under various fish migration conditions. The study then determines the surplus gain from cooperative management in comparison to non-cooperative management. The two surplus allocation rules, a rule based on Nash-bargaining and a rule based on stock distribution, are considered to determine the benefits from cooperative management for each country.

Third, this study shows that countries can achieve optimal management outcome through optimal pricing of fishing license fees. Because Pacific island states do not have sufficient domestic fishing capacity, the countries gain benefits from their fisheries resources by selling fishing access rights to distant water fishing nations' fleets. The paper derives an optimal pricing rule for fishing license fees under cooperative and non-cooperative regimes. I show that managers can attain optimal management in both settings by charging a fee based on the net price of the resource derived from the dynamic optimization.

For many migratory species, there may be large gains from managing the fish stocks through international cooperation. The 1995 United Nations Fish Stocks Agreement laid way for countries to manage such fish stocks through international cooperation (Bjørndal et al., 2000). The outcomes are the establishments of Regional Fisheries Management Organizations (RFMOs) such as the Western and Central Pacific Fisheries Commission and the International Commission for the Conservation of Atlantic Tuna (Meltzer, 2005). The RFMOs are comprised of both coastal states who have straddling and highly migratory species within their EEZs and distant water fishing nations who fish in international waters and foreign waters.

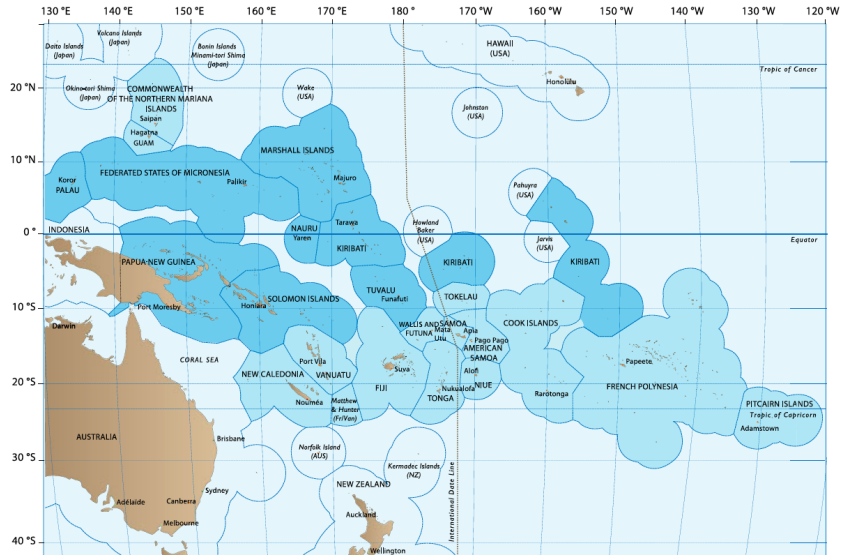
There are other regional international bodies that seek to cooperatively manage fish stocks. In the Western and Central Pacific, 17 coastal states formed the Forum Fisheries Agency (FFA) in 1979, preceding the UN Convention, to facilitate cooperation in managing their tuna stocks[1] (Hanich et al., 2010). What is notable here is that the FFA's membership is limited to coastal states only and was formed voluntarily to protect their asset, tuna, against distant water fishing nations. Since 1982, eight FFA members with tropical tuna fish stocks have agreed to cooperatively manage their tuna fisheries (Nauru Agreement, Figure 3.1). While the FFA does not have legally binding management measures, the Parties to the Nauru Agreement have successfully implemented legally binding regulations to manage purse-seine fisheries that target Skipjack tuna (Hanich et al., 2010).

The important policy question is how stock migration conditions would affect the benefits of such international agreement to manage migratory fish stocks. Furthermore, future climate change is predicted to alter migration patterns and distribution of fisheries resources (Lehodey et al., 2011; Sumaila et al., 2011). It is critical to examine whether cooperative management can withstand changes in resource stocks. To evaluate how cooperation gains perceived by individual countries change with climate change, it is essential to understand the link between fish migration and different management outcomes. This study aims to further the understanding of gains from cooperative management in relation to fish migrations.

Previous studies have examined the optimal management of straddling fish stocks by using a game theory framework. In particular, two studies build the foundation for the analysis of straddling stocks[2]. Munro (1979) uses Nash cooperative games to study the

[1] 17 countries are: Australia, Cook Islands, Federated States of Micronesia, Fiji, Kiribati, Marshall Islands, Nauru, New Zealand, Niue, Palau, Papua New Guinea, Samoa, Solmon Islands, Tokelau, Tonga, Tuvalu, Vanuatu.

[2] Aside from the two mentioned, there are several studies that play prominent roles in the economics of straddling fish stocks. Hannesson (1997) finds that when there are more agents sharing the resource, it gets more tempting to deviate and over-harvest. When stocks are distributed across boundaries and the migration of the stocks is limited, aggregate stock size plays a role in determining the threshold number of agents. When stocks straddle, and there are more smaller players as opposed to one leading player, the



Dark blue shows the EEZs of the Parties to the Nauru Agreement.
Map source: Bell et al. (2013)

Figure 3.1: Map of Parties to the Nauru Agreement

optimal management of renewable resources when two countries share a common fish stock. Joint management of a shared stock by the two countries may be obstructed if the two countries have different discount rates or harvesting costs. He argues that side payments enables the countries to overcome such obstructions and benefit from the joint management of shared fish stocks. Levhari and Mirman (1980) study Nash-Cournot duopolists who share a common fishery resource. If there is no agreement, each party's objective is to maximize the sum of discounted utility over time. Each party's harvesting decision will affect the common stock size when stock growth is assumed to take a form of logistic growth with dependence on stock escapement from the previous period. They find that if the two parties have a common interest in maximizing the sum of both parties' utilities, they can achieve higher consumption, and therefore higher utility, relative to the non-cooperative solution.

These early studies focused on cases where two countries share a common stock. Hence, "straddling" and "migrating" are not modeled precisely. More recently, McKelvey et al. (2006) and Golubtsov and McKelvey (2007) show a case where the stocks are split between two countries. In their model, a spawning takes place at some arbitrary location. After

efficiency loss is greater.

Laukkanen (2003) studies a sequential harvesting of fish stocks whose recruitments are affected by stochastic shocks. The two-country model considers fish that breed in 2's waters that migrate to 1's waters to feed. Because recruitment in 2's country would be affected by stochastic shocks, even country 2 follows the cooperative harvesting rule. Country 1 could misjudge country 2's behavior, which could lead them to deviate. In this study, cooperative management is defined as the "self-enforcing equilibrium" supported by the threat of harvesting non-cooperatively forever if deviations are detected.

stock recruitment, the stock splits and migrates to two countries' waters before fishing season starts. After the season ends, the stocks move back to the common spawning ground. This model of "split-stream harvesting" is applied to study Norwegian Spring-spawning herring (McKelvey et al., 2006).

Hannesson (2013) examines harvesting strategies of two countries under three stock migration models to analyze Northeast Atlantic mackerel. The countries differ in the share of stocks within their waters; it is assumed that one country has more than half of the combined stocks. The first model follows split-stream harvesting where each country gets a fixed share of the stocks. In this case, he finds that the country with more than half of the combined stocks (the major country) is required to offer some share to the minor country to achieve the global optimal, indicating strong bargaining power for the minor country. The other two models have variable migration, which means that the stock growth is influenced by stochastic shocks. Specifically, he analyzes a case when stock migration from the major country to the minor country depends on the size of the major country's stocks and a case when stock migration from the major country to the minor country is randomly determined. In the former case, the minor country's bargaining power is significantly reduced. In the latter case, the minor country retains the bargaining power.

These recent developments in modeling straddling and highly migratory fish stocks are good for representing seasonal migration patterns. In general, fish migration is dictated by a seasonal movement of fish that go to a certain location for spawning and another location for feeding. Tropical tuna species move to tropical waters to spawn and move to more temperate water to feed. However, this is not the only kind of fish migration. Some fish species such as Skipjack tuna move to waters with more abundant food (FAO Fisheries and Aquaculture Department, b).

Another approach to address spatial externalities that arise from fish migrations is through looking at fishing grounds in terms of "patches" that are spatially connected. Sanchirico and Wilen (1999) develops a framework that links spatial dispersal of fish and fishing effort under open access. Their study investigates different dispersal scenarios for fish movement. They consider patches in the fishing grounds that are inter-linked through spatial distribution of fish stocks [3].

Costello and Polasky (2008) extend the work by Sanchirico and Wilen to generalize the spatial renewable resource model with stochastic resource growth and dispersement to determine an optimal harvesting strategy. The model features spatial heterogeneity in terms

[3]Sanchirico and Wilen (1999) discusses that pelagic species's dispersal pattern can be categorized as fully integrated system where each patch is a source (i.e. location for biomass replenishment) and fish migrate across patches.

of economic cost and biological features [4]. Kaffine and Costello (2011) follow up on the work in Costello and Polasky (2008) to show a profit sharing mechanism, known as unitization, can achieve first-best outcome given property rights are assigned for each patch. That is, when patches are spatially connected, the harvesting behavior of a patch owner affects the profitability of others in the subsequent period. In such cases, full unitization, defined by full profit sharing, would achieve the optimal outcome [5]. These studies and the corresponding model of fisheries grounds as a "patchy environment" assumes that all the patches are owned by someone. In the Western and Central Pacific, there are patches of international waters where no country has ownership. Hence, not all the benefits from the resources can be captured. To address this, it is best to consider a resource stock dynamics where a portion of the fish stocks will migrate to international waters[6].

Ishimura et al. (2013) investigate management of Pacific sardine in the California Current System by using a three-country (Mexico, the United States, and Canada) game theoretic bioeconomic model under decadal scale climate variability. Using sea surface temperature as the key variable, they analyze cooperative behavior under cold water and warm water regimes. They find that cooperation achieves superior conservation and economic outcomes under both regimes[7].

In this study, I present an alternative model for managing straddling and highly migratory fish stocks. The focus of this study is non-seasonal movements of fish rather than seasonal migrations. Abundance of Skipjack tuna in one's waters depends on the availability of its feed. To describe this type of fish movement, I set up the resource constraint as a combination of stock growth and net migration from one's waters. Reflecting the fact that there are international waters with ill-defined rights surrounding the EEZs, the model allows some of the stock to out-migrate to area outside of any countries' exclusive economic zones. Kaffine and Costello (2011) extend the patchy environment framework to study optimal

[4]Costello and Polasky (2008) analyze both interior solutions and corner solutions of the model. The corner solution cases are determined to analyze policy questions surrounding the establishment of marine reserves.

[5]It is also striking that Kaffine and Costello (2011) show that full unitization can be achieved voluntarily with appropriate dividends.

[6]In addition to this, unitization may not be feasible because Pacific island states gain benefits from the tuna resources through the sales of fishing licenses to distant water fishing nations. Full unitization would mean that each individual Pacific island state contribute all of their revenues from the sales of fishing licenses, then distribute the pooled-revenues as dividends. Kaffine and Costello (2011) argues that patch owner with higher price (or lower marginal cost) would require higher dividends for voluntary participation. When countries are selling fishing licenses, these findings imply that countries who are able to capture a higher price for the access rights can gain higher dividends. This requires that each country report the result of their negotiations with distant water fishing nations' vessels. Disclosure of the negotiation outcomes may reduce their ability to set the license fee.

[7]Ishimura et al. (2013) note that they do not establish the stability of such cooperation, since it is beyond the scope of their study.

management of spatially connected resources. However, in their framework, it is presumed that rights are assigned to all the patches. This is not the case in the Western and Central Pacific.

Using this alternative resource constraint, I derive steady state harvest levels and stock levels under a cooperative management regime and a non-cooperative management regime with a two-country dynamic optimization model. I show a surplus gain from cooperative management in comparison to non-cooperative management by numerical illustration. Numerical illustration shows that countries may benefit from cooperation when there are migrations of fish. Because Pacific island states do not have sufficient domestic fishing capacity, they sell fishing access rights to distant water fishing nations' fleets. The paper shows that there is a positive relationship between the optimal price of fishing license and stocks.

It is known that El Niño events have impacts on the concentration of Skipjack tuna. During El Niño events, weak trade winds cause warmer water to spread farther to the east in the Central Pacific. This decreases upwelling intensity, which causes the relevant thermocline to deepen in the Central and Eastern Pacific and rise in the Western Pacific. This leads to increased Skipjack abundance in the region where the warm pool meets with the nutrient-rich Pacific Equatorial Divergence (Lehodey et al., 2011). Based on this observation, climate change studies predict a permanent eastward shift of Skipjack tuna (Lehodey et al., 2013). I conclude this paper by discussing climate change impacts on tropical tuna management in the Pacific island region.

3.2 Model

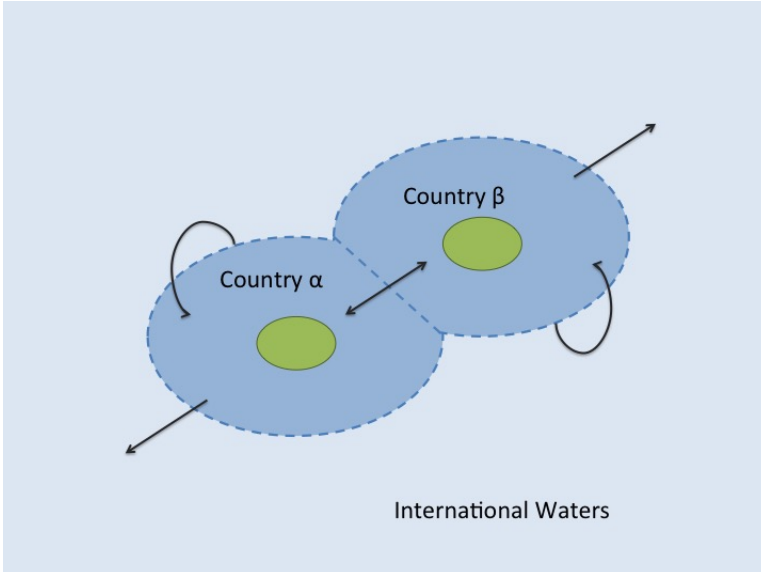
Suppose there are two countries α and β. Each country has fish stocks that move in and out of its waters. Now, suppose that in each period, there are some migrations of some fish from their waters. Let δ_t be a rate of migration for each time period that ends up in its neighbor's waters. There are also leakages of some fish to international waters surrounding the EEZs. Figure 3.2 shows a simple schematic of this stock condition. In the figure, there are two countries whose EEZs are adjacent to each other. Arrows represent migration movements.

The equation of motion for fish stocks, S_t, can be expressed as the following equations:

$$\dot{S_{\alpha,t}} = F(S_{\alpha,t}) - x_{\alpha,t} - \phi_\alpha \delta_{\alpha,t} S_{\alpha,t} + \delta_{\beta,t} S_{\beta,t}$$

$$\dot{S_{\beta,t}} = F(S_{\beta,t}) - x_{\beta,t} - \phi_\beta \delta_{\beta,t} S_{\beta,t} + \delta_{\alpha,t} S_{\alpha,t}.$$

In the equation, fish growth is expressed as $F(\cdot)$ and is a function of fish stocks. Subscripts α and β represent countries α and β. S_α represents α's stocks and S_β represents β's stocks.



Country α and β are neighboring island states whose EEZs are adjacent to each other. Arrows pointing outward represent stock leakages from their EEZs to international waters.

Figure 3.2: Schematic

Harvest by α and β are expressed as x_α and x_β. Total out-migration from $i = \alpha, \beta$ can be expressed as $\phi_i \delta_{i,t} S_{i,t}$ where $\phi_i \geq 1$ is a parameter representing leakages of fish to international waters[8]. Net migration for $i \neq j$ is expressed as $-\phi_i \delta_{i,t} S_{i,t} + \delta_{j,t} S_{j,t}$.

In this section, I present two-country models of straddling and highly migratory fish stock management. First, I present a regime where two countries cooperatively manage the stocks. Second, I present a regime where each country implements its own management non-cooperatively. I do this by setting up dynamic optimization problems for each regime. Steady state and dynamic paths of harvests and stocks for each regime under different stock migration scenarios are discussed in the following numerical illustration section.

3.2.1 Cooperative Management

First, let us consider a case where two countries manage their stocks cooperatively. Under cooperative management, a manager maximizes a sum of present values of net benefits from fisheries for both countries. Net benefits of fisheries in country i at time t can be expressed as

$$NB_{i,t} = px_{i,t} - c(S_{i,t})x_{i,t},$$

[8] $\phi = 1$ indicates a case that all the migration ends up in the neighbor's waters.

where the first term is a total revenue expressed by the product of an exogenous price of fish and harvests and the second term is a total cost expressed by a product of a unit cost of harvesting as a function of stocks and harvests. I am implicitly assuming that the two countries are price takers and harvest amounts would not affect the price of fish. This is equivalent to the assumption of a small-open economy.

The dynamic optimization problem for a cooperative management is

$$\begin{aligned}
\max_{x_{\alpha,t},x_{\beta,t}} \quad & \int_0^\infty e^{-\rho t}[px_{\alpha,t} + px_{\beta,t} - c(S_{\alpha,t})x_{\alpha,t} - c(S_{\beta,t})x_{\beta,t}]dt \\
\text{subject to} \quad & \dot{S_{\alpha,t}} = F(S_{\alpha,t}) - x_{\alpha,t} - \phi_\alpha\delta_\alpha S_{\alpha,t} + \delta_\beta S_{\beta,t} \\
& \dot{S_{\beta,t}} = F(S_{\beta,t}) - x_{\beta,t} - \phi_\beta\delta_\beta S_{\beta,t} + \delta_\alpha S_{\alpha,t} \\
& S_0 \text{ given} \\
& x_{i,t} \in [0, x^{\max}]
\end{aligned} \tag{3.1}$$

where ρ represents a discount rate.

To solve this problem, construct the Hamiltonian equation

$$\begin{aligned}
\mathbb{H} = px_{\alpha,t} + px_{\beta,t} - c(S_{\alpha,t})x_{\alpha,t} - c(S_{\beta,t})x_{\beta,t} \quad & +\lambda_t[F(S_{\alpha,t}) - x_{\alpha,t} - \phi_\alpha\delta_\alpha S_{\alpha,t} + \delta_\beta S_{\beta,t}] \\
& +\mu_t[F(S_{\beta,t}) - x_{\beta,t} - \phi_\beta\delta_\beta S_{\beta,t} + \delta_\alpha S_{\alpha,t}]
\end{aligned}$$

From the Maximum Principle, we can derive the following conditions:

$$\begin{aligned}
\frac{\partial \mathbb{H}}{\partial x_{\alpha,t}} &= p - c(S_{\alpha,t}) - \lambda_t = 0 \\
\frac{\partial \mathbb{H}}{\partial x_{\beta,t}} &= p - c(S_\beta) - \mu_t = 0 \\
\dot{\lambda_t} &= \rho\lambda_t + c'(S_{\alpha,t})x_{\alpha,t} - F'(S_{\alpha,t})\lambda_t + \phi_\alpha\delta_\alpha\lambda_t - \delta_\alpha\mu_t \\
\dot{\mu_t} &= \rho\mu_t + c'(S_{\beta,t})x_{\beta,t} - F'(S_{\beta,t})\mu_t + \phi_\beta\delta_\beta\mu_t - \delta_\beta\lambda_t \\
\dot{S_{\alpha,t}} &= F(S_{\alpha,t}) - x_{\alpha,t} - \phi_\alpha\delta_\alpha S_{\alpha,t} + \delta_\beta S_{\beta,t} \\
\dot{S_{\beta,t}} &= F(S_{\beta,t}) - x_{\beta,t} - \phi_\beta\delta_\beta S_{\beta,t} + \delta_\alpha S_{\alpha,t}.
\end{aligned} \tag{3.2}$$

Steady state stocks and harvests can be obtained by setting $\dot{\lambda_t} = \dot{\mu_t} = \dot{S_{\alpha,t}} = \dot{S_{\beta,t}} = 0$.

These equations reduce to two equations with two variables, S_α and S_β,

$$[\rho - F'(S_\alpha^C) + \phi_\alpha\delta_\alpha][p - c(S_\alpha^C)] - \delta_\alpha[p - c(S_\beta^C)] + c'(S_\alpha^C)[F(S_\alpha^C) - \phi_\alpha\delta_\alpha S_\alpha^C + \delta_\beta S_\beta^C] = 0 \tag{3.3}$$

$$[\rho - F'(S_\beta^C) + \phi_\beta\delta_\beta][p - c(S_\beta^C)] - \delta_\beta[p - c(S_\alpha^C)] + c'(S_\beta^C)[F(S_\beta^C) - \phi_\beta\delta_\beta S_\beta^C + \delta_\alpha S_\alpha^C] = 0. \tag{3.4}$$

It is important to note that the steady state stocks obtained by solving this joint maximization problem should not be translated directly as the cooperative management solution. To find the cooperation outcome, we must first determine the surplus gained from this joint maximization relative to non-cooperative management. After finding the surplus, we can determine how this surplus would be allocated between the two countries. This will typically involve side payments from one country to another. We discuss this further in the later section.

3.2.2 Non-cooperative Management

To find the surplus gained from cooperative management, we must first determine what would be the outcome when the two countries manage the stocks independently. Under non-cooperative management, each country maximizes its present value of net benefits. Dynamic optimizations yield steady state reaction functions for their stocks as a function of their neighbor's stocks.

Country α

Country α maximizes its net benefits by choosing its own harvests $x_{\alpha,t}$. A manager in α solves a dynamic optimization problem by taking stocks in β's waters as given. The maximization problem can be expressed as

$$\begin{aligned} \max_{x_{\alpha,t}} \quad & \int_0^\infty e^{-\rho t}[px_{\alpha,t} - c(S_{\alpha,t})x_{\alpha,t}]dt \\ \text{subject to} \quad & \dot{S_{\alpha,t}} = F(S_{\alpha,t}) - x_{\alpha,t} - \phi_\alpha \delta_\alpha S_{\alpha,t} + \delta_\beta \bar{S}_{\beta,t.} \\ & S_0 \text{ given} \\ & x_{i,t} \in [0, x^{\max}] \end{aligned} \tag{3.5}$$

To solve this problem, the Hamiltonian equation can be written as

$$\mathbb{H} = px_{\alpha,t} - c(S_{\alpha,t})x_{\alpha,t} + \lambda_{\alpha,t}[F(S_{\alpha,t}) - x_{\alpha,t} - \phi_\alpha \delta_\alpha S_{\alpha,t} + \delta_\beta \bar{S}_{\beta,t}].$$

By applying the Maximum Principle, the following conditions are derived:

$$\frac{\partial \mathbb{H}}{\partial x_{\alpha,t}} = p - c(S_{\alpha,t}) - \lambda_{\alpha,t} = 0 \tag{3.6}$$

$$\dot{\lambda_{\alpha,t}} = \rho\lambda_{\alpha,t} + c'(S_{\alpha,t})x_{\alpha,t} - \lambda_{\alpha,t}F'(S_{\alpha,t}) + \phi_\alpha \delta_\alpha \lambda_{\alpha,t}$$

$$\dot{S_{\alpha,t}} = F(S_{\alpha,t}) - x_{\alpha,t} - \phi_\alpha \delta_\alpha S_{\alpha,t} + \delta_\beta \bar{S}_{\beta,t}.$$

At the steady state, $\dot{S_{\alpha,t}} = 0$ and $\dot{\lambda_{\alpha,t}} = 0$. Solving the above equations at the steady state will yield

$$[\rho - F'(S^I_\alpha) + \phi_\alpha \delta_\alpha][p - c(S^I_\alpha)] + c'(S^I_\alpha)[F(S^I_\alpha) - \phi_\alpha \delta_\alpha S^I_\alpha + \delta_\beta \bar{S}_\beta] = 0. \tag{3.7}$$

By rearranging this, steady state $S_{\alpha,t}$ can be expressed as a function of $S_{\beta,t}$. I call this function a pseudo-reaction function for α at the steady state.

Country β

Country β also maximizes its net benefit by choosing its own harvest $x_{\beta,t}$ by taking the stocks in α's waters as given. Country β's dynamic optimization problem can be expressed as

$$\begin{aligned} \max_{x_{\beta,t}} \quad & \int_0^\infty e^{-\rho t}[p x_{\beta,t} - c(S_{\beta,t}) x_{\beta,t}] dt \\ \text{subject to} \quad & \dot{S_{\beta,t}} = F(S_{\beta,t}) - x_{\beta,t} - \phi_\beta \delta_\beta S_{\beta,t} + \delta_\alpha \bar{S}_{\alpha,t.} \\ & S_0 \text{ given} \\ & x_{i,t} \in [0, x^{\max}] \end{aligned} \tag{3.8}$$

The Hamiltonian equation can be expressed as

$$\mathbb{H} = p x_{\beta,t} - c(S_{\beta,t}) x_{\beta,t} + \mu_{\beta,t}[F(S_{\beta,t}) - x_{\beta,t} - \phi_\beta \delta_\beta S_{\beta,t} + \delta_\alpha \bar{S}_{\alpha,t}].$$

By applying the Maximum Principle,

$$\frac{\partial \mathbb{H}}{\partial x_{\beta,t}} = p - c(S_{\beta,t}) - \mu_{\beta,t} = 0 \tag{3.9}$$

$$\dot{\mu_{\beta,t}} = \rho \mu_{\beta,t} + c'(S_{\beta,t}) x_{\beta,t} - \mu_{\beta,t} F'(S_{\beta,t}) + \phi \delta_\beta \mu_{\beta,t}$$

$$\dot{S_{\beta,t}} = F(S_{\beta,t}) - x_{\beta,t} - \phi_\beta \delta_\beta S_{\beta,t} + \delta_\alpha \bar{S}_{\alpha,t}.$$

At the steady state, $\dot{S_{\beta,t}} = 0$ and $\dot{\mu_{\beta,t}} = 0$. Solving the above equations at the steady state will yield

$$[\rho - F'(S^I_\beta) + \phi_\beta \delta_\beta][p - c(S^I_\beta)] + c'(S_\beta)[F(S^I_\beta) - \phi_\beta \delta_\beta S^I_\beta + \delta_\alpha \bar{S}_\alpha] = 0. \tag{3.10}$$

By rearranging this, steady state $S_{\beta,t}$ can be expressed as a function of $S_{\alpha,t}$. I call this function a pseudo-reaction function for β.

3.2.3 Steady State Characteristics

Steady state stocks under the cooperative management regime can be obtained where equations (3.3) and (3.4) intersect. Equilibrium and steady state stocks under the non-cooperative management regime can be obtained where the two pseudo-reaction functions intersect. This can be found by solving equations (3.7) and (3.10). To compare and characterize the outcomes under cooperative and non-cooperative management, take a close look at the four equations.

Proposition 3.2.1. *Suppose $p > c(S^I)$ and $p > c(S^C)$, and steady state stock under cooperative management and non-cooperative management falls above the maximum sustainable yield. If $S_i^I > S_i^C$ and $S_j^I > S_j^C$, it must be that $x_i^C > x_i^I$.*

Proof. By definition, $c'(\cdot) < 0$ and $c''(\cdot) > 0$. Also, $F'(\cdot) < 0$ and $F''(\cdot) < 0$ when the stock growth function takes the form of the usual concave shaped curve. By equation (3.3) and (3.4),

$$[\rho - F'(S_i^C) + \phi_i\delta_i][p - c(S_i^C)] + c'(S_i^C)[F(S_i^C) - \phi_i\delta_i S_i^C + \delta_j S_j^C] = \delta_i[p - c(S_j^C)].$$

By definition, the right hand side of this equation is positive. By equation (3.7)) and (3.10)),

$$[\rho - F'(S_i^I) + \phi_i\delta_i][p - c(S_i^I)] + c'(S_i)[F(S_i^I) - \phi_i\delta_i S_i^I + \delta_j \bar{S}_j] = 0.$$

Comparing the the first term in the left hand side of the two equations,

$$[\rho - F'(S_i^C) + \phi_i\delta_i][p - c(S_i^C)] < [\rho - F'(S_i^I) + \phi_i\delta_i][p - c(S_i^I)]$$

Comparing the second term, because $c'(S_i^C) < c'(S_i^I$ given $c''(\cdot) > 0$ and $S_i^I > S_i^C$, it must be that

$$F(S_i^C) - \phi_i\delta_i S_i^C + \delta_j S_j^C > F(S_i^I) - \phi_i\delta_i S_i^I + \delta_j \bar{S}_j.$$

At the steady state,

$$x_i^C = F(S_i^C) - \phi_i\delta_i S_i^C + \delta_j S_j^C,$$

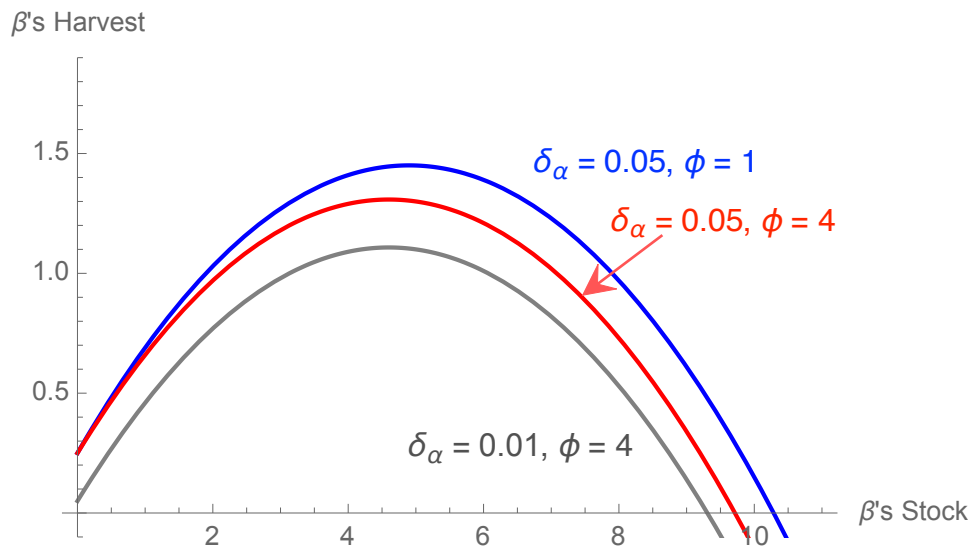
and

$$x_i^I = F(S_i^I) - \phi_i\delta_i S_i^I + \delta_j \bar{S}_j.$$

Therefore, if $S_i^I > S_i^C$ and $S_j^I > S_j^C$, then $x_i^C > x_i^I$.

□

This, however, is not a typical situation. In most cases, we would expect to find that



Notes: Parameter values are set at $\gamma = 0.5$, $\kappa = 10$, and $\delta_\beta = 0.01$, and α's stock is fixed at $S_\alpha = 5$

Figure 3.3: Sustainable Yield Curve for β

cooperation conserves more stocks compared to non-cooperative management. In order to further characterize the differences between cooperative and non-cooperative management, the following section shows the steady state stocks and harvests through numerical illustration.

3.3 Numerical Illustration

To compare steady state stocks and harvests under cooperative and non-cooperative regimes, I assume the unit cost of harvesting to take a form

$$c(S_t) = \frac{\theta}{S_t}.$$

The unit cost of harvesting is assumed to be an inverse function of stocks with a parameter $\theta > 0$. The unit cost of harvesting is equal to the marginal cost of harvest because the total cost of harvest is a linear function of harvest, $TC_t = c(S_t)x_t$. This function satisfies that $c'(S) < 0$ and $c''(S) > 0$, which implies that the unit cost of harvesting decreases as stocks increase and is concave.

The stock growth function takes the standard logistic function form:

$$F(S) = \gamma S\Big(1 - \frac{S}{\kappa}\Big),$$

where γ is the intrinsic growth rate and κ is the carrying capacity. Parameters are set at $\rho = 0.02, p = 2, \theta = 3, \gamma = 0.5, \kappa = 10^9$.

3.3.1 Steady State

Figure 3.3 shows the sustainable yield curve for the resource constrained presented in this study. The curve shows a steady state relationships between harvests and stocks for β, where $\dot{S}_\beta = 0$. The horizontal axis shows stocks for β and the vertical axis shows harvests for β. The logistic growth curve gives us the inverse U-shaped graph. If there is no migration, the graph intersects with the horizontal axis at zero and κ, the carrying capacity parameter, which is specified to be $\kappa = 10$. Given α's stocks and β's migration rate, an increase in α's migration rate moves the graph outwards, and an increase in β's stock leakage parameter shifts the graph downwards.

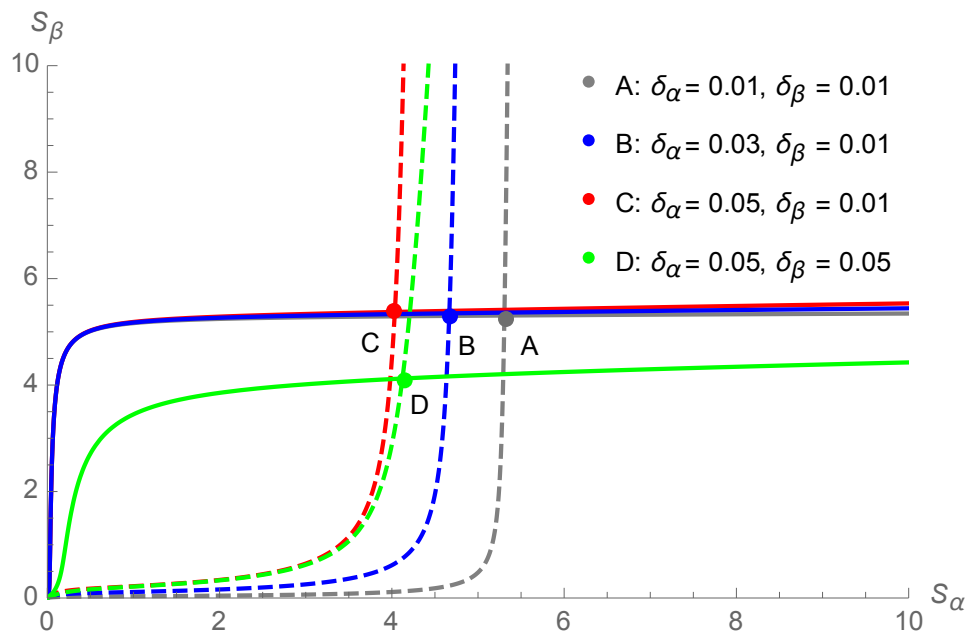
Figure 3.4 shows the stocks under cooperation at the steady state. The figure shows the equations (3.3) and (3.4) with different combinations of stock migration rates. By holding β's stock migration rate constant, α's graph shifts to the left as its stock migration rate increases (compare A, B, and C). Change in α's migration rates shift the graph for β upwards as well. If the two countries have the same stock migration rate (compare A and D), higher migration rate is shown to reduce the size of lens created by the two graphs. This indicates smaller steady state stocks. This result comes from the model set up, where the stock leakage is linearly correlated with the stock migration within the two countries. If we suppose that there is no stock leakage to international waters, the steady state would be the same when the two countries have the same migration rates.

Figure 3.5 shows steady state stock relationships under non-cooperative management obtained by solving conditions derived from the Maximum Principle that are presented in Section 3.2.2 with different migration rates. Pseudo reaction functions for a country i at the steady state can be expressed in terms of its own stocks as a function of the neighbor country j's stocks. This can be represented by

$$S_i = R(S_j)$$

for $i \neq j$. Solid lines show pseudo reaction functions for β. Dashed lines show pseudo reaction functions for α with varying migration rates, $\delta_\alpha = 0.01, 0.03$, and 0.05. An increase in its own migration rate pushes α's pseudo steady state reaction function inwards. Holding β's migration rate constant at $\delta_\beta = 0.01$, the graphs show that equilibrium steady state stocks

[9]Note also that if fisheries operate as open access, we have zero net benefit so that $p = c(S)$. With the given unit cost function and parameter values, we have stocks under an open access regime $S^{OA} = 1.5$.



Notes: Dashed lines represent equation (3.3) and solid lines represent equation (3.4). Parameter values are set at $\gamma = 0.5$, $\kappa = 10$, $p = 2$, $\theta = 3$, and $\theta = 4$..

Figure 3.4: Steady State Stocks (Cooperative Management)

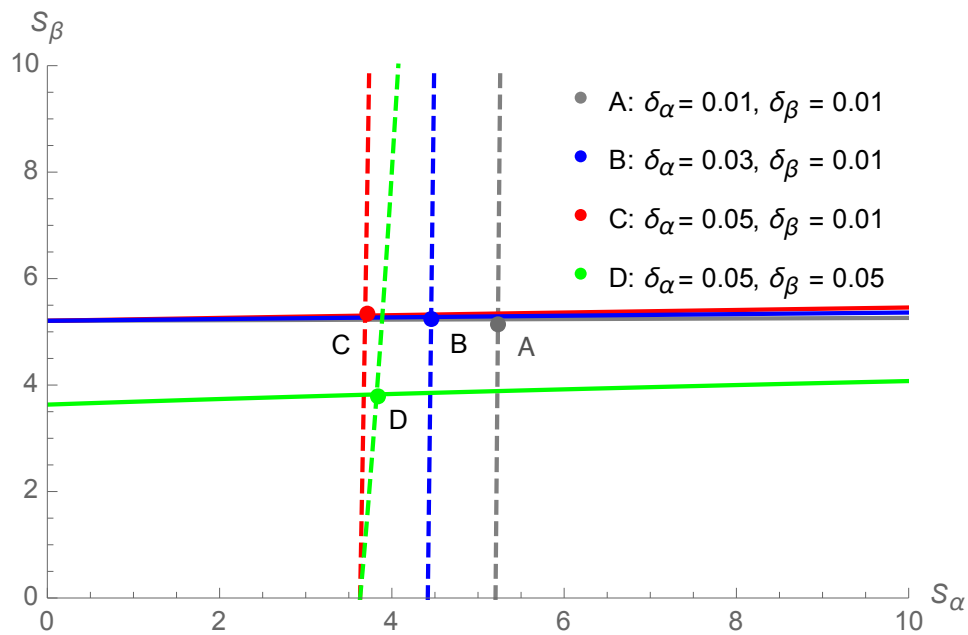
for α decrease as α's migration rate increases. Equilibrium steady state stocks for β decrease as well, though not as much as α's.

Table 3.1 presents stocks and harvests at the steady state. The left panel shows steady state solutions under cooperative management. The right panel shows the steady state solutions under non-cooperative management. Different combinations of leakage rates to international waters (ϕ) and migration rates (δ) are examined. When there is no migration (i.e. $\delta_\alpha = \delta_\beta = 0$,), cooperative management and non-cooperative management yield equivalent results.

From Table 3.1, we are able to observe that an increase in leakage rates reduces steady state stock levels. When the two countries have the same migration rates, by comparing two sets of migration rate parameters $\delta_\alpha = \delta_\beta = 0.01$ and $\delta_\alpha = \delta_\beta = 0.05$, we find that lower migration rates correspond to higher steady state stocks and harvests under both management regimes. Higher levels of leakages of stocks to international waters result in smaller steady state stocks and harvests.

3.3.2 Dynamic Approach Paths to the Steady State

Because this paper assumes a perfectly elastic demand curve (i.e. fixed price), the transition to the steady-state is of "bang-bang." That is, if the initial stock is above the steady state,



Notes: Dashed lines represent equation (3.7) and solid lines represent equation (3.10). Parameter values are set at $\gamma = 0.5$, $\kappa = 10$, $p = 2$, $\theta = 3$, and $\theta = 4$..

Figure 3.5: Steady State Stocks (Non-cooperative Management)

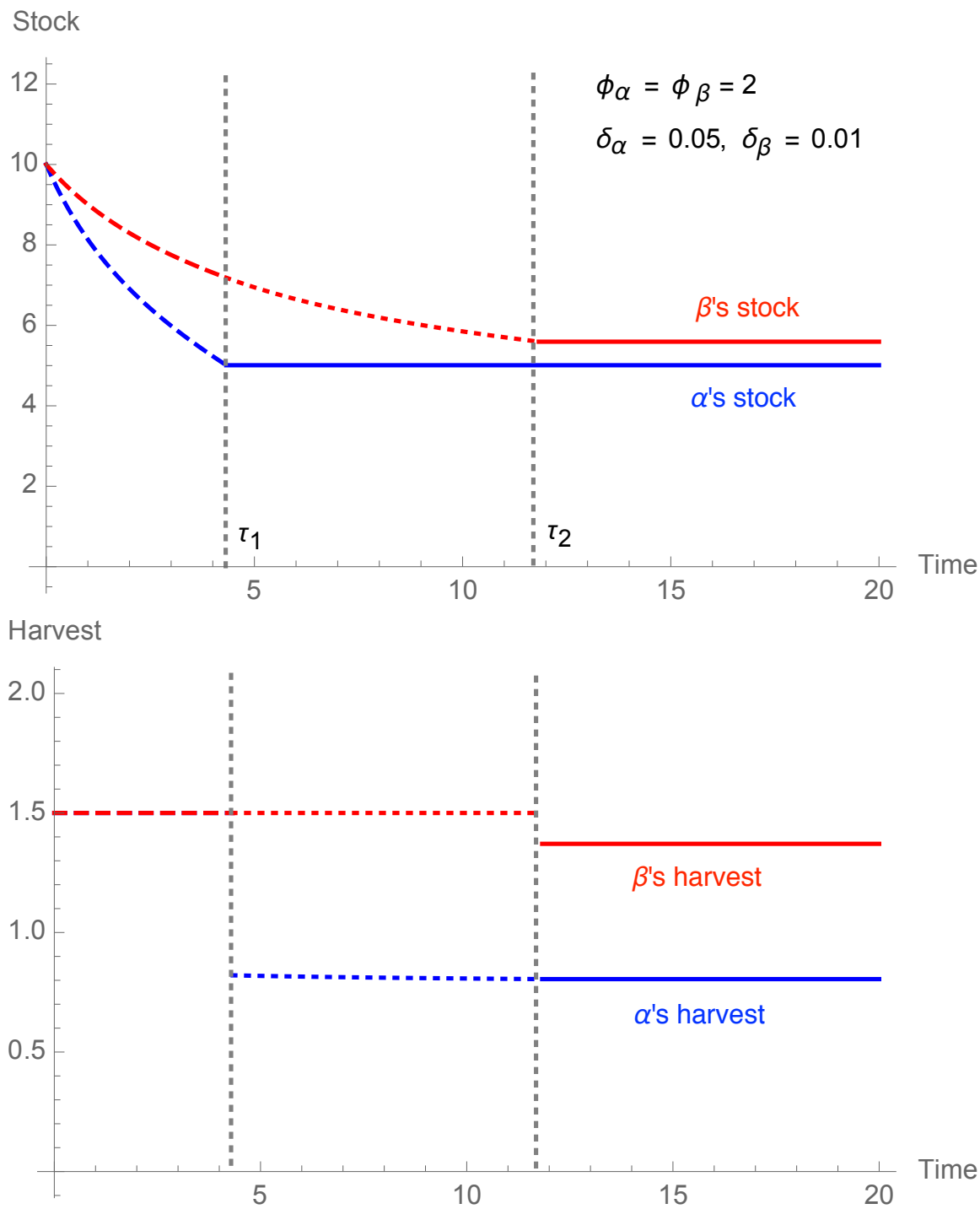
optimal harvest would be a harvest at the maximum rate. If the initial stock is below the steady state, optimal harvest would be zero (Spence and Starrett, 1975). This can be expressed as the following where superscript s.s. signifies steady state values.

$$x_{i,t} = \begin{cases} x^{\max} & \text{if } S_{i,t} > S^{\text{s.s.}} \\ 0 & \text{if } S_{i,t} < S^{\text{s.s.}} \end{cases}$$

At the steady state where $s_{i,t} = s^{\text{s.s.}}$, we have $x_{i,t} = x^{\text{s.s.}}$.

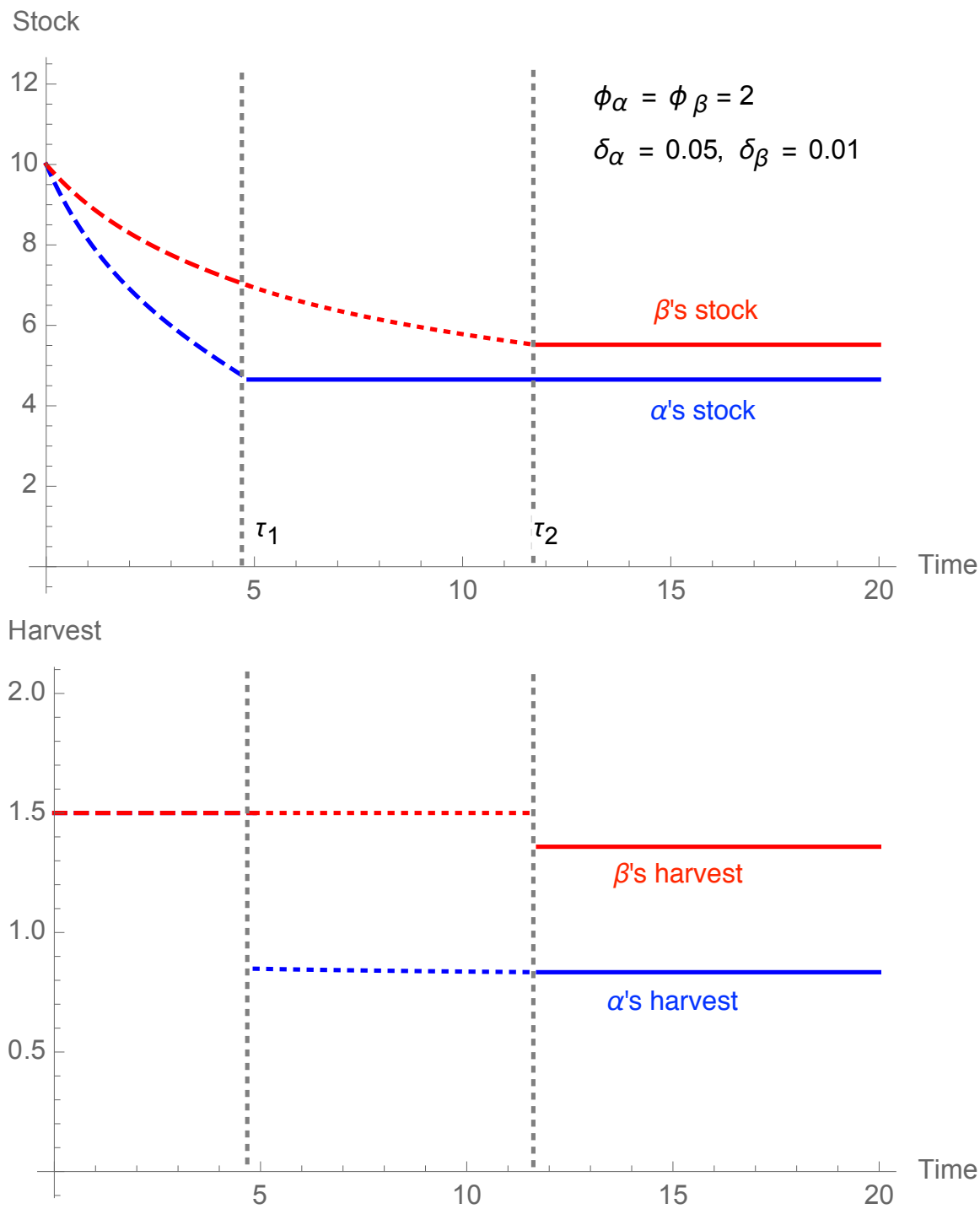
Figure 3.6 and 3.7 respectively show typical dynamic paths to the steady state under cooperative management and non-cooperative management. The figures show the case when the countries have different migration rates, $\delta = 0.05$ and $\delta = 0.01$. In both figures, the top panel shows the stock paths, and the bottom panel shows the harvest paths. As I mentioned earlier, because the model assumes perfectly elastic demand, the harvesting path is of "bang-bang."

The figures represent the case when initial stocks for the two countries are above the steady state stock levels. In this case, the two countries harvest at the maximum capacity until stocks reach steady state levels. Dynamic paths depicted in the figure indicate that country α, whose migration rate is higher than the other country, reaches its steady state first. This is not a true steady state, however, inasmuch as harvest level is decreasing slightly



Notes: $\delta_\alpha = 0.05$, $\delta_\beta = 0.01$ The graphs show transition paths to the steady state under cooperative management when two countries have different migration rates. Maximum harvest level ($x^{\max}$) is set at 1.5. Dashed lines show the stock paths for $t = [0, \tau_1)$, dotted lines show the approach paths for $t = [\tau_1, \tau_2)$, and the solid lines show the approach paths for $t = [\tau_2, \infty]$. Parameter values are set at $\gamma = 0.5$, $\kappa = 10$, $p = 2$, and $\theta = 3$. Initial stock is set at $S_0 = 9.999$. With the given parameters and functional forms, $\tau_1 = 4.32$ and $\tau_2 = 11.83$.

Figure 3.6: Dynamic Paths under Cooperative Management when Initial Stock is Near the Carrying Capacity



Notes: $\delta_\alpha = 0.05$, $\delta_\beta = 0.01$ The graphs show transition paths to the steady state under non-cooperative management when two countries have different migration rates. Maximum harvest level ($x^{\max}$) is set at 1.5. Dashed lines show the stock paths for $t = [0, \tau_1)$, dotted lines show the approach paths for $t = [\tau_1, \tau_2)$, and the solid lines show the approach paths for $t = [\tau_2, \infty]$. Parameter values are set at $\gamma = 0.5$, $\kappa = 10$, $p = 2$, and $\theta = 3$. Initial stock is set at $S_0 = 9.999$. With the given parameters and functional forms, $\tau_1 = 4.86$ and $\tau_2 = 11.73$.

Figure 3.7: Dynamic Paths under Non-cooperative Management when Stock is Near the Carrying Capacity

Table 3.1: Steady State Stocks and Harvests

Cooperative Management						Non-cooperative Management					
$\phi_\alpha = \phi_\beta = 1$						$\phi_\alpha = \phi_\beta = 1$					
δ_α	δ_β	S_α	S_β	x_α	x_β	δ_α	δ_β	S_α	S_β	x_α	x_β
0.01	0.01	5.604	5.604	1.232	1.232	0.01	0.01	5.531	5.531	1.236	1.236
0.03	0.01	5.551	5.654	1.125	1.339	0.03	0.01	5.336	5.581	1.140	1.337
0.05	0.01	5.501	5.702	1.019	1.443	0.05	0.01	5.140	5.625	1.048	1.431
0.05	0.05	5.604	5.604	1.232	1.232	0.05	0.05	5.250	5.250	1.247	1.247
$\phi_\alpha = \phi_\beta = 2$						$\phi_\alpha = \phi_\beta = 2$					
δ_α	δ_β	S_α	S_β	x_α	x_β	δ_α	δ_β	S_α	S_β	x_α	x_β
0.01	0.01	5.505	5.505	1.182	1.182	0.01	0.01	5.433	5.433	1.186	1.186
0.03	0.01	5.256	5.552	0.987	1.281	0.03	0.01	5.042	5.481	1.002	1.280
0.05	0.01	5.009	5.594	0.805	1.371	0.05	0.01	4.653	5.519	0.834	1.359
0.05	0.05	5.109	5.109	0.994	0.994	0.05	0.05	4.770	4.770	1.009	1.009
$\phi_\alpha = \phi_\beta = 4$						$\phi_\alpha = \phi_\beta = 4$					
δ_α	δ_β	S_α	S_β	x_α	x_β	δ_α	δ_β	S_α	S_β	x_α	x_β
0.01	0.01	5.307	5.307	1.086	1.086	0.01	0.01	5.236	5.236	1.090	1.090
0.03	0.01	4.667	5.347	0.738	1.170	0.03	0.01	4.457	5.279	0.753	1.169
0.05	0.01	4.034	5.373	0.450	1.230	0.05	0.01	3.690	5.305	0.479	1.218
0.05	0.05	4.123	4.123	0.593	0.593	0.05	0.05	3.825	3.825	0.607	0.607
$\phi_\alpha = 1$, $\phi_\beta = 2$						$\phi_\alpha = 1$, $\phi_\beta = 2$					
δ_α	δ_β	S_α	S_β	x_α	x_β	δ_α	δ_β	S_α	S_β	x_α	x_β
0.01	0.01	5.603	5.505	1.231	1.183	0.01	0.01	5.531	5.433	1.235	1.187
0.03	0.01	5.550	5.558	1.124	1.290	0.03	0.01	5.335	5.485	1.139	1.289
0.05	0.01	5.499	5.607	1.019	1.394	0.05	0.01	5.140	5.530	1.047	1.382
0.05	0.05	5.581	5.133	1.211	1.015	0.05	0.05	5.238	4.784	1.224	1.031
$\phi_\alpha = 2$, $\phi_\beta = 1$						$\phi_\alpha = 2$, $\phi_\beta = 1$					
δ_α	δ_β	S_α	S_β	x_α	x_β	δ_α	δ_β	S_α	S_β	x_α	x_β
0.01	0.01	5.505	5.603	1.183	1.231	0.01	0.01	5.433	5.531	1.187	1.235
0.03	0.01	5.258	5.648	0.988	1.330	0.03	0.01	5.042	5.577	1.003	1.329
0.05	0.01	5.012	5.689	0.806	1.420	0.05	0.01	4.653	5.614	0.835	1.408
0.05	0.05	5.133	5.581	1.015	1.211	0.05	0.05	4.784	5.238	1.031	1.224

Note: ϕ is a parameter representing leakage to international waters, where $\phi = 1$ indicates no leakages of stocks to international waters. δ is a parameter representing migration rate. S represents steady state stocks. x represents steady state harvests. Other parameter values are set at $\gamma = 0.5$, $\kappa = 10$, $p = 2$, and $\theta = 3$.

to compensate for the lower influx from country α[10]. Comparing the dynamics of cooperative and non-cooperative management, we find that cooperative management reaches the steady state earlier than non-cooperative management. This derives from the fact that cooperative management has higher steady state stock levels. It is also important to note that when the two countries have different fish migration and stock leakage conditions, one of them reaches the steady state stock first, while the other country's stock continues on to the steady state. In this transition period, the country which reached the steady state first maintains the steady state stock level by adjusting its harvest level. The harvest in this period would be a sum of its steady state harvest amount and the excess migration from the neighboring country's waters. Once both countries reach the steady state, they harvest exactly the steady state harvest amount. The detailed calculation used to obtain these dynamics is explained in Appendix A.

3.3.3 Surplus Gained from Cooperative Management

Table 3.2 shows the present value of net benefits calculated for different stock dynamic scenarios when the initial stock is near the carrying capacity. The left panel shows the present value of net benefits under cooperative management and the right panel shows the present value of net benefits under non-cooperative management. Surplus gained from cooperation relative to non-cooperative management is listed in the right most column.

From Table 3.2, we find that there is a gain from cooperatively managing the stocks even when the two countries have the same migration rates and there are no leakages of stocks to international waters. We also find that leakages reduce cooperation surplus. In Table 3.2, the difference between the two scenarios when $\phi_\alpha = \phi_\beta = 2$ and $\phi_\alpha = \phi_\beta = 4$ is that the latter has a leakage that is three times greater than the former. By comparing the two, we find that higher leakage rate is associated with reduced surplus gain from cooperation. For all combinations of leakage parameters, by comparing the migration rates combination $\delta_\alpha = 0.03, \delta_\beta = 0.01$ and $\delta_\alpha = 0.05, \delta_\beta = 0.01$, we see that the latter has the greater surplus gain from cooperation. When $\phi_\alpha = 1$ and $\phi_\beta = 2$, for the first three combinations of migration parameters (i.e. $\delta_\alpha = \delta_\beta = 0.01, \delta_\alpha = 0.03, \delta_\beta = 0.01,$ and $\delta_\alpha = 0.05, \delta_\beta = 0.01$), the amount of leakage from the joint management area to international waters is the same. This is also true for the case when $\phi_\alpha = 2$ and $\phi_\beta = 1$ with the migration parameter combinations $\delta_\alpha = 0.05, \delta_\beta = 0.01$ and $\delta_\alpha = \delta_\beta = 0.05$. Under such circumstance, we find

[10]Time paths of shadow prices are discussed in Roumasset and Tarui (2013). They point out that shadow price dynamics are not equal to the dynamics of shadow price expressions derived by following Maximum Principle (i.e Equations 3.2, 3.6, and 3.9) in the bang-bang case. This is simply because the equalities assumed in the equations do not hold where stock, $s_{i,t}$, is greater than the steady state level of stock as $x_{i,t} = x^{\max}$ as long as the stock is greater than the steady state level.

that surplus gain increases with the increase in the gap between the two countries migration parameters.

Now, let us consider how the two countries allocate the surplus gained from cooperative management. Previous literature suggest a few alternative allocation methods. Let us first consider a rule based on Nash-bargaining. Under Nash-bargaining, the two countries solve the problem

$$\begin{aligned} \max_{\pi_\alpha, \pi_\beta} \quad & (\pi_\alpha - \pi_\alpha^I)^\sigma (\pi_\beta - \pi_\beta^I)^{1-\sigma} \\ \text{subject to} \quad & \pi_\alpha + \pi_\beta = \bar{\pi}, \end{aligned} \tag{3.11}$$

where π represent the present value of net benefits, and σ represents bargaining power . Further, suppose that $\sigma = \frac{1}{2}$. I take bargaining power to be equal since there are no alternative partners and either party can veto the agreement. The Nash-bargaining solution is summarized in Table 3.3 (See Appendix for the calculation detail of the Nash-bargaining solution). The left columns show the allocation based on the Nash-bargaining rule. The right columns show the allocation proportionate to the stock distribution between the two countries. Under the proportionate rule, each country receives the present value of net benefits obtained from solving the joint maximization problem described in Section 3.2.1.

Under the Nash-bargaining rule, the surplus gained from cooperative management is equally shared between the two countries. Under the proportionate rule, a country with a higher migration rate gains from the cooperation more than the other. By comparing the cases when the two countries have the same leakage parameter value, an increase in leakage parameters for the two countries reduces the share of surplus gained by α, a country with higher migration rates under the proportionate rule.

3.4 Implications for Tropical Tuna Management in the Western and Central Pacific

The Western and Central Pacific region provides a vast tuna fishery grounds. Tropical species of tuna – Skipjack, Yellowfin, and Bigeye tuna – are caught for canned tuna and for higher-grade sashimi markets. Purse-seine vessels are used mainly to catch Skipjack and Yellowfin tuna for canned tuna markets. Longline vessels are used to catch Yellowfin and Bigeye tuna for sashimi markets. While purse-seine vessels operate within the EEZs of Pacific island states, longline vessels commonly operate near the equator, in international waters (Langley et al., 2009; Hanich et al., 2010). Distant water fishing nations play prominent roles in tuna fisheries in the Western and Central Pacific; vessels from East Asia (Japan, Taiwan, South Korea), the Americas (the U.S., Chile), and Europe (Spain) travel to this region to catch

Table 3.2: The Present Value of Net Benefits and Surplus Gained from Cooperation

Cooperative Management			Non-cooperative Management					
$\phi_\alpha = \phi_\beta = 1$			$\phi_\alpha = \phi_\beta = 1$					
δ_α	δ_β	NPB_{Total}	δ_α	δ_β	NPB_α	NPB_β	NPB_{Total}	Surplus
0.01	0.01	188.578	0.01	0.01	90.257	90.257	180.513	8.064
0.03	0.01	188.459	0.03	0.01	81.036	101.679	182.715	5.744
0.05	0.01	188.089	0.05	0.01	66.696	108.329	175.025	13.064
0.05	0.05	188.578	0.05	0.05	93.760	93.760	187.520	1.058
$\phi_\alpha = \phi_\beta = 2$			$\phi_\alpha = \phi_\beta = 2$					
δ_α	δ_β	NPB_{Total}	δ_α	δ_β	NPB_α	NPB_β	NPB_{Total}	Surplus
0.01	0.01	180.558	0.01	0.01	90.257	90.257	180.513	0.045
0.03	0.01	172.766	0.03	0.01	71.129	97.120	168.249	4.517
0.05	0.01	165.378	0.05	0.01	55.368	102.783	158.151	7.1226
0.05	0.05	150.178	0.05	0.05	74.574	74.574	149.148	1.030
$\phi_\alpha = \phi_\beta = 4$			$\phi_\alpha = \phi_\beta = 4$					
δ_α	δ_β	NPB_{Total}	δ_α	δ_β	NPB_α	NPB_β	NPB_{Total}	Surplus
0.01	0.01	165.017	0.01	0.01	82.486	82.486	164.972	0.044
0.03	0.01	144.067	0.03	0.01	53.121	88.236	141.357	2.711
0.05	0.01	127.049	0.05	0.01	32.448	91.832	124.280	2.768
0.05	0.05	87.157	0.05	0.05	43.163	43.163	86.325	0.832
$\phi_\alpha = 1$, $\phi_\beta = 2$			$\phi_\alpha = 1$, $\phi_\beta = 2$					
δ_α	δ_β	NPB_{Total}	δ_α	δ_β	NPB_α	NPB_β	NPB_{Total}	Surplus
0.01	0.01	184.343	0.01	0.01	93.930	90.333	184.263	0.080
0.03	0.01	184.457	0.03	0.01	82.805	97.761	180.566	3.891
0.05	0.01	184.154	0.05	0.01	70.621	104.475	175.096	9.058
0.05	0.05	168.942	0.05	0.05	91.389	76.244	167.632	1.309
$\phi_\alpha = 2$, $\phi_\beta = 1$			$\phi_\alpha = 2$, $\phi_\beta = 1$					
δ_α	δ_β	NPB_{Total}	δ_α	δ_β	NPB_α	NPB_β	NPB_{Total}	Surplus
0.01	0.01	184.343	0.01	0.01	90.333	93.930	184.263	0.080
0.03	0.01	176.770	0.03	0.01	69.696	101.043	170.739	6.031
0.05	0.01	169.337	0.05	0.01	53.112	106.665	159.777	9.560
0.05	0.05	168.942	0.05	0.05	76.244	91.389	167.632	1.309

Note: ϕ is a parameter representing leakage to international waters. δ is a parameter representing migration rate. S_0 represents initial stocks and is set at $S_0 = 9.999$. NPB represents the present value of net benefits. Other parameter values are set at $\gamma = 0.5$, $\kappa = 10$, $p = 2$, and $\theta = 3$.

Table 3.3: The Present Value of Net Benefits under Cooperation

		Nash-bargaining Rule				Proportionate Rule			
$\phi_\alpha = \phi_\beta = 1$									
δ_α	δ_β	PNB_α	% share	PNB_β	% share	PNB_α	% share	PNB_β	% share B
0.01	0.01	94.289	50%	94.289	50%	94.289	50%	94.289	50%
0.03	0.01	83.908	50%	104.551	50%	86.386	93%	102.073	7%
0.05	0.01	73.228	50%	114.861	50%	78.636	91%	109.453	9%
0.05	0.05	94.289	50%	94.289	50%	94.289	50%	94.289	50%
$\phi_\alpha = \phi_\beta = 2$									
δ_α	δ_β	PNB_α	% share	PNB_β	% share	PNB_α	% share	PNB_β	% share
0.01	0.01	90.279	50%	90.279	50%	90.279	50%	90.2791	50%
0.03	0.01	73.388	50%	99.379	50%	75.250	91%	97.5164	9%
0.05	0.01	58.982	50%	106.396	50%	61.450	84%	103.928	16%
0.05	0.05	75.089	50%	75.089	50%	75.089	50%	75.089	50%
$\phi_\alpha = \phi_\beta = 4$									
δ_α	δ_β	PNB_α	% share	PNB_β	% share	PNB_α	% share	PNB_β	% share
0.01	0.01	82.508	50%	82.508	50%	82.508	50%	82.5083	50%
0.03	0.01	54.476	50%	89.591	50%	55.439	86%	88.6283	14%
0.05	0.01	33.832	50%	93.216	50%	34.093	59%	92.9557	41%
0.05	0.05	43.579	50%	43.579	50%	43.579	50%	43.5785	50%
$\phi_\alpha = 1$, $\phi_\beta = 2$									
δ_α	δ_β	PNB_α	% share	PNB_β	% share	PNB_α	% share	PNB_β	% share
0.01	0.01	93.970	50%	90.373	50%	93.989	73%	90.354	27%
0.03	0.01	84.751	50%	99.706	50%	86.307	90%	98.1498	10%
0.05	0.01	75.150	50%	109.004	50%	78.549	88%	105.605	12%
0.05	0.05	92.043	50%	76.899	50%	92.233	64%	76.709	36%
$\phi_\alpha = 2$, $\phi_\beta = 1$									
δ_α	δ_β	PNB_α	% share	PNB_β	% share	PNB_α	% share	PNB_β	% share
0.01	0.01	90.373	50%	93.970	50%	90.354	27%	93.989	73%
0.03	0.01	72.712	50%	104.058	50%	75.326	93%	101.444	7%
0.05	0.01	57.892	50%	111.445	50%	61.528	88%	107.809	12%
0.05	0.05	76.899	50%	92.043	50%	76.709	36%	92.2328	64%

Note: ϕ is a parameter representing leakage to international waters. δ is a parameter representing migration rate. S_0 represents initial stocks and is set at $S_0 = 9.999$. NPB represents the present value of net benefits. Other parameter values are set at $\gamma = 0.5$, $\kappa = 10$, $p = 2$, and $\theta = 3$.

tuna. There are also vessels from nearby coastal states. However, their capacities are limited compared to distant water fishing nations' vessels.

Efforts to cooperatively manage tuna fisheries in the Western and Central Pacific region precede the 1982 Convention on Law of the Sea. In 1979, the Forum Fisheries Agency (FFA) was formed by 17 coastal states in the Western and Central Pacific[11]. The main objective of the FFA is to support sustainable tuna fisheries activities through cooperation among the coastal states (Hanich et al., 2010; Havice, 2010). While it does not directly manage the fisheries, the FFA provides services that allow its member states to implement management measures [12].

In 1983, seven Pacific island states with the most productive EEZs among the FFA members formed an agreement in Nauru to cooperatively manage the tuna in their waters (Hanich et al., 2010; Havice, 2010) [13]. These countries are referred to as the Parties to the Nauru Agreement (the PNA, Table 3.4). The Parties manage 14.3 million km^2 of ocean. Tuna in the PNA's management area are valued at $2 billion per year and account for 30% of the global tuna supply (The Pew Charitable Trusts). Because the Parties do not have large domestic fishing capacities, they grant access to distant water fishing nations to catch their tuna stocks in return for monetary compensation (Havice, 2010; Miller, 2007). This cooperative management helps increase bargaining power for the Parties when they negotiate with distant water fishing nations for the terms of access agreements (Havice, 2013).

In 1993, the Parties formed a legally binding tuna management agreement (the Palau Agreement), partly to limit the number of purse-seine vessels within their EEZs. This was the first legally binding international tuna management agreement in the region[14]. To strengthen management, in 2007, the Parties adopted the Vessel Day Scheme. Under the scheme, the Parties set annual limits on the number of fishing days (Total Allowable Efforts) within the PNA managed waters. The Parties allocate the Total Allowable Efforts among

[11]See the list of its members in the footnote on page 42.

[12]This kind of voluntary international cooperation to manage tuna stocks is rare. Libecap (2014) praises tuna management in the Western and Central Pacific by comparing to the case of Atlantic tuna. He attributes the successful cooperation to a relative homogeneity across Pacific island states. There is a counter-argument, however, noted by Cartwright et al. (2000) that atoll nations in the region have limited income alternatives aside from the tuna fisheries while other larger island nations have other income sources such as timber and minerals.

[13]To protect the rights over their rich resources, Pacific island states established their EEZs in the late 1970s (Havice and Campling, 2010). The EEZ regime was officially recognized and codified in the 1982 United Nations Convention on Law of the Sea. The EEZ regime granted coastal states sovereign rights to the resources within 200 nautical miles of their shores. This regime gave sovereign rights over fish stocks, including straddling and highly migratory stocks. This supported newly independent Central and Western Pacific island states' economies by securing their rights to gain benefits from their valuable fisheries resources, which were previously exploited to benefit distant water fishing nations.

[14]It is debatable whether the limits introduced by the Palau Agreement are binding (Hanich et al., 2010; Havice, 2010). Some claim that the limits are higher than equilibrium levels, and therefore, the fisheries operate as if they are open access. In addition, previous studies have shown the ineffectiveness of limited entry programs to manage effort inputs in fisheries (Wilen, 1979).

Table 3.4: Parties to the Nauru Agreement

	GDP per capita (USD)	Population	EEZ (km^2)
Federated State of Micronesia	3,235	103,500	2,992,597
Kiribati	1,651	102,400	3,437,345
Marshall Islands	3,325	52,630	1,992,232
Nauru	6,954	10,000	308,502
Papua New Guinea	2,088	7,321,000	2,396,214
Palau	11,810	20,920	604,289
Solomon Islands	1,954	561,200	1,597,492
Tuvalu	3,861	9,876	751,797

Note: GDP per capita is in current USD. GDP per capita and population data are taken from the World Bank (http://data.worldbank.org/) for the year 2013 except for Nauru. Nauru GDP per capita and population data are taken from the United Nations (http://data.un.org/) for the year 2011. EEZ is in km^2 and is taken from Sea Around Us Project (http://www.seaaroundus.org/).

themselves (Parties Allowable Efforts) based on the historical record and the current stock in their EEZs (Dunn et al., 2006). Each individual country then individually negotiates with a distant water fishing nation to sell the fishing days within the limit of its Parties Allowable Efforts (Hanich et al., 2010). The Vessel Day Scheme is applied to all purse-seine vessels that operate in the EEZs of the Parties and the high sea enclaves surrounded by the PNA's EEZs. Negotiation between a Party and a distant water fishing nation is done bilaterally, with the exception of the US, which successfully negotiated multi-access agreements with 16 Pacific island countries in 1983 (Havice, 2010). This indicates that a Party can charge different prices to different distant water fishing nations. Meanwhile, a distant water fishing nation may pay different prices to different Parties. The Parties are also allowed to trade their Parties Allowable Efforts among themselves. There are several cases of such trades since the start of the VDS (Dunn et al., 2006). In most cases, the trades were necessitated when a member ran out of fishing days in the middle of the season (World Wildlife Fund, 2011).

3.4.1 Optimal Tariffs Charged to Foreign Vessels

Because Pacific island states do not have sufficient domestic fishing capacities, they sell fishing access rights to distant water fishing nations. In other words, foreign vessels need to pay a fee to operate in their EEZs. Under the current management by the PNA and the Vessel Day Scheme, access rights are sold per fishing day basis. Distant water fishing nations' vessels are required to pay a fee for each fishing day to the Party in whose waters

the vessels operate.

To find an optimal price of a fishing day, first consider a distant water fishing nations' vessels' profit maximization problem. A representative vessel j's profit can be expressed as

$$\Pi_{i,j} = px_{i,j} - c(S_i)x_{i,j} - \eta_i d_{i,j}.$$

In the equation, $x_{i,j}$ denotes harvests in i's EEZ by vessel j. The total fee paid to country i is a product of the price of a fishing day, η_i, and the number of fishing days purchased, $d_{i,j}$.

Suppose a production function takes a form so that harvests by j in i's waters is a linear function of fishing days, $x_{i,j} = \nu d_{i,j}$ where $\nu > 0$ represents the average harvest per day. The profit maximization problem can be expressed as

$$\max \Pi_{i,j} = p\nu d_{i,j} - c(S_i)\nu d_{i,j} - \eta_i d_{i,j}.$$

Taking the first order condition with respect to $d_{i,j}$,

$$p = c(S_i) + \frac{\eta_i}{\nu}.$$

Hence,

$$\eta_i = \nu(p - c(S_i)) \tag{3.12}$$

For managers to achieve optimal management, they charge access fees equal to the product of the amount harvested per day and the net price. In a sense, the access fee acts as a landing tax for the foreign vessels. If the fee is optimally set, the net price is equal to the marginal user cost. In order to determine the optimal license fee, managers gather information about the price of fish, the stock level, and the harvesting cost function. If harvest per day, ν, is not homogeneous across different vessels, more productive vessels would be charged higher fees. Indeed, this is the case under the current Vessel Day Scheme, where larger vessels with higher catching capacity are charged higher fees and smaller vessels are charged lower fees.

It is natural to assume that net price is higher when stock levels are higher. We can also expect that the average daily harvest is higher when the stock levels are higher. Because the optimal fishing license fee is a product of net price and average daily harvest, we can expect to find higher optimal fishing license fees when the stock levels are higher.

3.4.2 Climate Change Implications on Optimal License Fees

Climate change inevitably impacts fisheries. It results in changes in the productivity of fish stocks, migration patterns, and overall community composition (Sumaila et al., 2011).

Changes in distribution of fish stocks indicates changes in stock densities, which has significant economic implications McIlgorm (2010). In particular, in the Western and Central Pacific, eastward shift of Skipjack tuna, the most important tuna resource in the region, is predicted (Lehodey et al., 2013). The studies also predict that climate change will lead to increased tuna abundance in the Western and Central Pacific regions in the near-term. However, this trend is temporary, and by 2050, we see some of the countries experiencing a tuna decrease in their waters. By 2100, we see diverging trends: some countries have more tuna in their waters compared to 2008 while others have less tuna in their waters (Bell et al., 2013; Lehodey et al., 2013).

Table 3.5: Predicted Climate Change Impacts on Skipjack Tuna Stock Distribution

	% Change in Stock			VD Allocation
Parties to the Nauru Agreement	2035	2050	2100	2008
Federated State of Micronesia	+14 %	+5 %	-16 %	5,986 days
Marshall Islands	+24 %	+24 %	+10 %	2,676 days
Nauru	+25 %	+20 %	-1 %	1,362 days
Palau	+10 %	+2 %	-27 %	568 days
Papua New Guinea	+3 %	-11 %	-30 %	8,209 days
Solomon Islands	+3 %	-5 %	-15 %	2,413 days
Kiribati	+37 %	+43 %	+24 %	6,130 days
Tuvalu	+37 %	+41 %	+25 %	961 days

Note: Stock distribution prediction from Lehodey et al. (2011) cited in Bell et al. (2013). 2008 Fishing Day Allocation from Aqorau (2009).

Table 3.5 shows the expected impacts of climate change on Skipjack tuna distribution and the Vessel Day allocation in 2008. Plus signs indicate an increase in stock within the respective EEZs, and minus signs indicate a decrease in stock within the respective EEZs. The table shows that diverging impacts of climate change can be observed for different countries. For instance, countries such as Kiribati expect increased stocks, while countries such as Papua New Guinea expect decreased stocks within its EEZs. Comparing these two countries, as of 2008, Papua New Guinea has more stock than Kiribati. Assuming that the Vessel Day allocations are adjusted to tuna stock assessments, Kiribati's Vessel Day allocation surpasses Papua New Guinea's by the year 2050[15]. The previous section on optimal fishing license fees show that there is a positive relationship between stock and license fees. This indicates that climate change winners would also gain from being able to charge higher fishing license fees. On the other hand, climate change losers would incur

[15]The current Vessel Day Scheme rule determines the allocation of the vessel days among its members based on the historical catch record as well as stock assessment.

significant loss of income.

3.5 Conclusion and Discussion

This study presents a model of cooperative management for straddling and highly migratory fish stocks, focusing on non-seasonal movements and leakages of fish stocks to international waters. The study shows that stock leakage to international waters reduce the surplus gain from cooperative management. For a given stock leakage, the cooperation surplus increases with an increase in the gap in migration rates between the two countries.

To arrive at this conclusion, the two-country dynamic optimization problems are solved to show the steady state stocks and harvests under cooperative and non-cooperative management first. Under cooperative management, a manager maximizes a combined sum of the present values of net benefits from the fisheries in the two countries. The manager solves the problem by choosing harvests for each country. Under non-cooperative management, each country's manager maximizes the present value of net benefits from its fisheries by choosing harvests. Fish dynamics, defined by logistic stock growth and net migration, are used to describe trans-boundary fish movements.

Numerical illustration shows the steady state stocks and harvests for various migration rate parameters. The surplus gain from cooperative management over non-cooperative management is derived by comparing the present value of net benefits under non-cooperative management and cooperative management. The study confirms that cooperative management is beneficial when there is spatial externality created by fish migration. This is true even when the two countries have the same migration rates and no stocks leak out to international waters. The study presents two alternative methods of calculating surplus gain from cooperation. By definition, under the Nash-bargaining rule, the two countries split the surplus in half. Side payments from a country with higher migration rates to the other country may facilitate the cooperation. Under the allocation rule based on the stock distribution between the two countries, a country with higher migration rates gains more from cooperation.

The stock growth and migration model considered in this study differs from the split-stream harvesting model considered by Golubtsov and McKelvey (2007) and the migration models considered by Hannesson (2013). The major difference is that this study's model assumes that the stocks in the two countries are mutually dependent. The resource constraint presented in this paper is close to the framework of patchy environment suggested by Sanchirico and Wilen (1999). This framework is also used by Costello and Polasky (2008) and Kaffine and Costello (2011) to examine optimal harvesting with spatial externalities.

The major deviation from their studies and this study is that this study considers the case when some stock leaks out to the area where property rights are ill-defined. Because the EEZs of the Western and Central Pacific island countries are surrounded by the international waters, it is beneficial to determine the impacts of stock leakages.

The study also shows that countries are able to achieve optimal management through fishing license fees. In the Western and Central Pacific island region, because the countries do not have sufficient domestic fishing capacities, they gain benefits from the fisheries resource through the sales of fishing rights to distant water fishing nations. Currently, the countries issue licenses on a per day basis. In this case, the countries are able to achieve the optimal management outcome by setting the fee equal to the product of catch per day and net price.

The Western and Central Pacific is an important tuna fishing grounds. Under the Vessel Day Scheme by the PNA, the Parties charge fees per day of fishing operation. The revenues from the sale of fishing days have been an important revenue source for many coastal states in the Western and Central Pacific. Increased revenues from the fishing access rights in recent years have contributed to GDP growth for the Pacific island countries (Lucich and Lototele, 2014). Currently, the PNA set a price floor on the price of a fishing day. Their management objective appears to be to increase the revenue from the fishing day sales by acting as an oligopoly. The model suggests that each coastal state should set their fees according to the stock levels within their waters. Hence, the PNA should be allowed to set prices independently of each other.

This paper assumes that distant water fishing nations' vessels pay fishing access fees. This is true for distant water fishing nations such as Japan. However, this is not always the case. For instance, the EU government is paying the fee for the EU vessels at the moment. This would result in a sub-optimal outcome. In such cases, optimal pricing of fishing license fees would not lead to optimal management outcomes. Future research should investigate how differences in terms of negotiation between coastal states and distant water fishing nations' vessels would impact the price of fishing licenses and harvest.

This paper's model suggests that there is a positive relationship between an optimal fishing license fee and stock. In other words, countries with higher stock levels are able to charge higher fees to attain optimal management. Previous studies indicate that there will be winners and losers as the climate changes. Some countries will gain more stocks within their waters, while others will lose. Climate change impacts on fisheries income would not be trivial. If we assume that the average daily harvest is impacted by the stock size, the impacts of stock distribution change on fisheries income could be exacerbated.

In the present model, a country's stock leakages to international waters is set up as a multiple of migration from its waters to the neighboring country's waters. An alternative

set up to this is to decouple the leakage and migration rates. This alternative set up may be used to analyze the impacts of stock leakages to international waters independently from the migration within the countries' waters.

This study assume leakage and migration parameters are not time variant. This may not necessarily be the case. In addition to the climate change, the existing studies show that tropical tuna fisheries are impacted by shorter-term climate variabilities (Miller, 2007). In particular, El Niño Southern Oscillation (ENSO) events shift distribution of tuna stocks both horizontally and vertically. For instance, in the El Niño years, purse-seine catches typically increase in the Central Pacific, notably in the waters of Kiribati (Lehodey et al., 2011, 1997). In the La Niña years, the catchability of Yellowfin and Bigeye tuna decreases because the vertical band of their habitat widens and thereby reduces stock densities (Lehodey et al., 2011). Future studies should address the impacts of climate events on the benefits derived from cooperative management by using time-varying migration rates, including scenarios of sudden jumps and drops in migration rates.

Appendix A: Calculation of Approach Paths and Present Value of Net Benefits

This section explains the calculation used to determine stock approach paths to the steady state and corresponding the present value of net benefits. The calculation procedure to get the paths to the steady states is the same for cooperative and non-cooperative management, while the steady state values are different for the two management regimes. In the following, * denotes steady state values.

When the two countries have the same migration and leakage parameters

When the two countries have the same migration and leakage parameters (i.e. $\delta_i = \delta_j$ and $\phi_i = \phi_j$, from symmetry, we can rewrite the stock equation of the motion in country i as

$$\dot{S_{i,t}} = F(S_{i,t}) - x_{i,t} - (\phi_i - 1)\delta_i S_{i,t}.$$

To derive the switching timing to the steady state (τ), rearrange the equation of motion so that

$$\dot{S_{i,t}} = \frac{dS_i}{dt} = F(S_{i,t}) - x_{i,t} - (\phi_i - 1)\delta_i S_{i,t}$$

$$dt = \frac{dS_i}{F(S_{i,t}) - x_{i,t} - (\phi_i - 1)\delta_i S_i}$$

When $S_{i,0} < S_i^*$, MRAP is to harvest the maximum amount until the stock reaches the steady state. By integrating both sides to obtain τ,

$$\tau = \int_{S_{i,0}}^{S_i^*} \frac{1}{F(w) - x^{\max} - (\phi_i - 1)\delta_i w} dS_i.$$

The denominator in the right hand side of the equation takes the linear quadratic form, $aw^2 + bw + c$, where $a = -\frac{\gamma}{\kappa}$, $b = \gamma - (\phi_i - 1)\delta_i$, and $c = -x^{\max}$. The switching timing to the steady state, τ, can be solved by applying the integration rule for the inverse of linear quadratic function,

$$\int \frac{1}{aw^2 + bw + c} dw = \frac{2}{\sqrt{4ac - b^2}} \arctan\left(\frac{2aw + b}{\sqrt{4ac - b^2}}\right) + \text{constant}$$

evaluated for the range of S_i from $S_{i,0}$ to S_i^C. We can solve for the switching timing τ as

$$\tau(S_{i,0}, S_i^*, x^{\max}) = A\big(\arctan(BS_i^* + D) - \arctan(BS_{i,0} + D)\big)$$

where $A = \dfrac{2}{\sqrt{\dfrac{4\gamma x^{\max}}{\kappa} - (\gamma - (\phi_i - 1)\delta_i)^2}}$, $B = \dfrac{\dfrac{-2\gamma}{\kappa}}{\sqrt{\dfrac{4\gamma x^{\max}}{\kappa} - (\gamma - (\phi_i - 1)\delta_i)^2}}$,
and $D = \dfrac{\gamma - (\phi_i - 1)\delta_i}{\sqrt{\dfrac{4\gamma x^{\max}}{\kappa} - (\gamma - (\phi_i - 1)\delta_i)^2}}$.

The stock path to the steady state can be obtained by expressing $S_{i,t}$ as a function of t so that

$$S_{i,t} = \frac{\tan\frac{t}{A} + \arctan(BS_{i,0} + D) - D}{B}.$$

The present value of net benefits under cooperative management and non-cooperative management can be obtained by solving

$$\text{NPB} = \int_0^{\tau} e^{-\rho t}(p - c(S_{i,t}))x^{\max} + \int_{\tau}^{\infty} e^{-\rho t}(p - c(S_i^*))x^*$$

When the two countries have different migration and leakage parameters

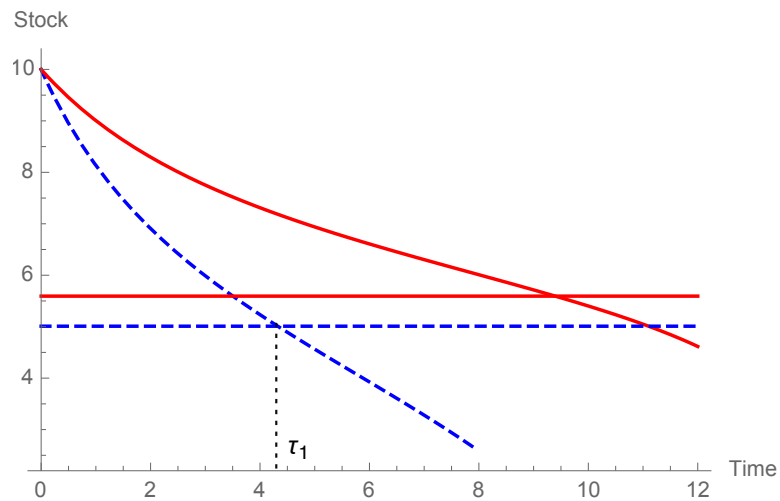
When the two countries have different parameters and/or leakage parameters, the above approach does not work. This is because the stock equation of motion involves the other country's stock, which is time variant. For this reason, in order to determine the switching timing, the two stock equations of motion need to be solved simultaneously. By assuming that the initial stock is above the steady state level, we can express the system of differential equations as

$$\dot{S_{i,t}} = F(S_{i,t}) - x^{\max} - \phi_i\delta_i S_{i,t} + \delta_j S_{j,t}$$

$$\dot{S_{j,t}} = F(S_{j,t}) - x^{\max} - \phi_j\delta_j S_{j,t} + \delta_i S_{i,t}.$$

By solving the system of differential equations, we are able to obtain $S_{i,t}$ for each of the countries. Figure 3.8 shows a typical solutions to the two equations of motion, along with steady states. Because the two equations have different migration parameters, their stocks reach the steady state at different times. The first switching time, τ_1 is the earliest time at which a path intersects with its steady state line. In the case depicted in Figure 3.8, τ_1 can be found where the blue dashed lines intersect.

Now, I suppose that once one of the stocks reaches the steady state, it stays at the steady



Notes: $\delta_i = 0.05$ (blue, dashed), $\delta_i = 0.01$ (red, dashed), $\phi_i = \phi_j = 2$, cooperative management.

Figure 3.8: Stock Paths Determined by Solving the Two Equations of Motion

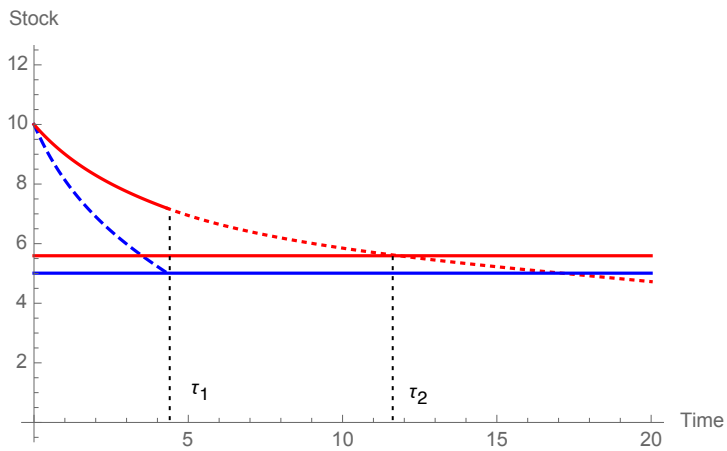
state. Suppose that country i reaches the steady state first. At this time, i's harvest drops from $x^{\max}$. After reaching τ_1, j's path also alters. It is important to note that j's stock is above steady state at this point. Denoting the switch time when both countries reach the steady state as τ_2, in the time frame $t = [\tau_1, \tau_2)$, the stock equation of motion for j becomes

$$\dot{S_{j,t}} = F(S_{j,t}) - x^{\max} - \phi_j \delta_j S_{j,t} + \delta_i S_i^*.$$

Figure 3.9 shows the paths after τ_1 for country j as a dotted line. τ_2 can be found where this line intersects with the steady state.

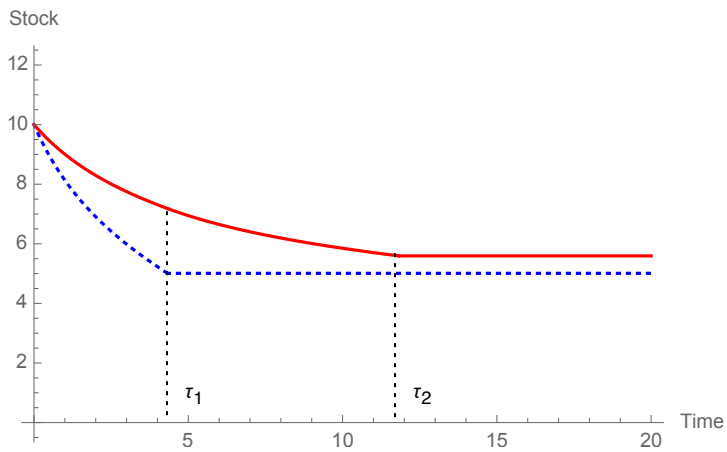
As I described earlier, I suppose that i's stock stays at the steady state level after the time reaches τ_1. At this point, we have $\dot{S_{i,t}} = 0$. This indicates that $x_{i,t} = F(S_i^c) - \phi_i \delta_i S_i^C + \delta_j S_{j,t}$, and $\dot{x_{i,t}} = \delta_j \dot{S_{j,t}}$. Now, let $S_{j,t} = S_j^C + \epsilon_{j,t}$. In Figure 3.9, ϵ_j is shown as the vertical difference between the red dotted line and the horizontal red solid line for the time region $t = [\tau_1, \tau_2)$. Now, we can express the harvest for i as

$$\begin{aligned} x_{i,t\in[\tau_1,\tau_2)} &= F(S_i^C) - \phi_i \delta_i S_i^C + \delta_j S_{j,t} \\ &= F(S_i^C) - \phi_i \delta_i S_i^C + \delta_j (S_j^C + \epsilon_{j,t}) \\ &= x_i^C + \delta_j \epsilon_{j,t}. \end{aligned}$$



Notes: $\delta_i = 0.05$ (blue), $\delta_i = 0.01$ (red), cooperative management, $\phi_i = \phi_j = 2$

Figure 3.9: Stock Approach Paths up to $\tau 2$



Notes: $\delta_i = 0.05$ (blue, dotted), $\delta_i = 0.01$ (red), $\phi_i = \phi_j = 2$, cooperative management

Figure 3.10: Example Stock Approach Paths to the Steady State

Hence, present net benefit for the each country can be calculated as

$$\text{PNB}_i = \int_0^{\tau_1} e^{-\rho t}(p - c(S_{i,t}))x^{\max}dt + \int_{\tau_1}^{\tau_2} e^{-\rho t}(p - c(S_i^*))x_{i,t}dt + \int_{\tau_2}^{\infty} e^{-\rho t}(p - c(S_i^*))x_\alpha^* dt$$

$$\text{PNB}_j = \int_0^{\tau_2} e^{-\rho t}(p - c(S_{j,t}))x^{\max}dt - \int_{\tau_2}^{\infty} e^{-\rho t}(p - c(S_j^*))x_j^* dt$$

where stock dynamics are depicted in Figure 3.10. In the figure, the stock approach path for i is depicted by a blue dashed line, and the stock approach path for j is depicted by a red line.

Appendix B: Nash-bargaining Solution

To solve the problem (3.13), from $\bar{pi} = \pi_\alpha + \pi_\beta$, plug $\pi_\beta = \bar{\pi} - \pi_\alpha$ into the equation (3.13)

$$\max_{\pi_\alpha} \quad (\pi_\alpha - \pi_\alpha^I)^{\frac{1}{2}}(\bar{\pi} - \pi_\alpha - \pi_\beta^I)^{\frac{1}{2}} \tag{3.13}$$

Take the first order condition with respect to π_α and get

$$\pi_\alpha = \frac{1}{2}(\bar{\pi} + \pi_\alpha^I - \pi_\beta^I).$$

π_β can be obtained from $\pi_\beta = \bar{\pi} - \pi_\alpha$.

Chapter 4

Institutional Evolution in Fisheries Management: Scarcity and the Intensity of Governance

4.1 Introduction

In the introduction to this dissertation, I discussed that some renewable resources, if left unmanaged, can be completely exhausted. The commercial fishery resource has long been managed under open access, which has led the world's fisheries to overharvest, resulting in excessive resource depletion. Not only does open access lead to resource depletion, but it also results in rent dissipation (Gordon, 1954). Economists have pointed to ill-defined property rights as the source of the problem. In the case of fisheries, the rights to the fish are only granted after the fish are harvested. Until then, no one owns the fish (*Farae Naturae*). Hence, to correct the problems associated with open access fishing, one needs to define and assign rights to the resource. This has been the principle governing the modern fishery.

Some fisheries have successfully adopted a rights-based management regime. Rights-based management such as individual transferable quota management aim to correct the problems associated with open access by assigning harvesting rights to individual fishermen. Iceland adopted an individual transferable quota regime in 1985, a management regime which allocated a portion of quota to individual vessels (Eythórsson, 2000). New Zealand adopted an individual transferable quota system as its national policy in 1986 (Newell et al., 2002). In the United States, there are 15 programs as of 2014 that allocate the shares to individual fishermen or groups of fishermen (National Oceanic and Atmospheric Administration).

Many others have adopted measures to alleviate over-harvesting by limiting the number

of fishery participants (limited entry), and by limiting the number of fish to be caught per season (catch quota). These management regimes could help alleviate problems associated with over-harvesting. However, studies have shown that limited entry or catch quota fail to generate economic rent because of individual incentives to race for fish (Grimm et al., 2012; Wilen, 1979; Costello et al., 2010). It is also shown that regulated open access, such as catch quota, may worsen the economics of the fishery (Homans and Wilen, 1997). Despite these findings, many fisheries still operate under open access or regulated open access regimes, and this is a puzzle.

This study investigates the puzzle of why many fisheries operate under what are apparently sub-optimal management regimes. The paper presents a theoretical framework to show institutional evolutions in fishery management by examining three key management institutions: open access, catch quota, and individual transferable quota. The study characterizes and explain institutional evolution scenarios for the three management regimes. I argue that allegedly inefficient management policy, such as a catch quota regime, may be being adopted as an intermediary step before the fishery adopts more efficient rights-based management, such as an individual transferable quota regime. In fact, many fisheries that adopted rights-based management such as individual transferable quota management have taken multiple steps before adopting such management Reimer and Wilen (2013). This could be explained by different management regimes incur different governance costs. While catch quota is touted as an inefficient management regime due to its failure to generate economic rent, it is relatively easy to implement compared to individual transferable quota. In other words, a less efficient but inexpensive management regime may be adopted before a more efficient but costly management regime is adopted. Which management institution to use when? This is the ultimate question that this study attempts to answer.

This study contributes to the literature of institutional change in resource management. Open access fisheries, if left unmanaged, could result in stock collapse. At the same time, Ostrom (2010) suggests that institutions could emerge to govern such resources to achieve sustained resource use. The question is: what are the conditions under which resource governance is instituted? Initial work on institutional change in the resource management sector derives from Demsetz (1967), who implied the endogeneity of assigning property rights. He states "whether or not the more complete defining of property rights is socially beneficial depends on the magnitude of common pool losses, the nature of contracting costs to resolve them, and the cost of defining and enforcing property rights." Anderson and Hill (1975) also argue that institutional change happens when the marginal cost of the change is equal or greater than the marginal benefit brought by the change.

Libecap (1999) lists shifts in relative price, changes in production and enforcement tech-

nology, and shifts in preferences and other political parameters as motivations for an institutional change. This argument is in-line with the view that institutional change happens when the benefit of the change exceeds the cost, implying that there may be conditions that cause delay or quicken the adoption of rights-based management.

Further, Libecap (2009) points out that one of the weaknesses of rights-based management is the delay in the assignment of property rights. Libecap (2007b) notes that rights-based management may easily be adopted if the value of the resource is high and the information cost necessary for the design and allocation of the rights is low. He argues that the assignment of property rights in fisheries may be delayed due to the difficulty inherent in reaching agreements on how to properly allocate the shares. For instance, one may argue that the rights should be given out based on historical catch. This, of course, makes it difficult for new entrants to enter the fishery. Because the allocation issue has to do with how individuals view "fair allocation" while everyone tries to maximize their own rent, rights-based institutions are hard to implement (Libecap, 2009, 2007a,b).

While these studies offer insights into understanding under what conditions institutional change occurs, these studies do so by without utilizing dynamic optimization tools. Copeland and Taylor (2009), on the other hand, develops a formal model to discuss under what conditions optimal management would prevail at the steady state. Roumasset and Tarui (2013) extend this effort by focusing on the transition to the steady state. Specifically, Roumasset and Tarui (2013) present a model of dynamic resource governance, where institutional change is induced by resource scarcity. While Roumasset and Tarui (2013) consider dynamic resource governance with a one-time institutional change from open access to some resource governance, this study specifically examines two fisheries management regimes; catch quota and individual transferable quota, and their sequential institutional changes. Under a catch quota regime, a manager limits the amount of harvest per season. Under an individual transferable quota regime, individuals are assigned shares of the catch quota for the season and are allowed to trade the shares with one another. I compare the scenario where a fishery goes through sequential transitions from an open access to an individual transferable quota regime via catch quota as an intermediary step to the scenario when a fishery goes directly from an open access to an individual transferable quota regime.

Catch share is an umbrella term for various rights-based fisheries management institutions. Two prime examples are the individual transferable quota regime and the territorial use rights regime. Compared to regulated open access regimes, such as limited entry or catch quota, catch share regimes attempt to correct incentives for fishermen not to race for fish. Under limited entry, an individual fisherman who has the license to harvest in the fishery has an incentive to increase their capacity to catch more. Under catch quota, an individual

fisherman races to catch more than other fishermen in the fishery in order to catch as much as possible before the fishery as a whole reaches its pre-determined fishery-wide catch quota. Because catch share programs assign shares of quota prior to the season, they help eliminate harvesters' incentives to race.

While catch share is the most advanced management tool present, it is not perfect. Arnason (2012) points out that catch share, in particular individual transferable quota, does not cover all aspects of property rights. Costello and Deacon (2007) also point out that stock heterogeneity such as heterogeneous stock densities across sub-groups of stocks in a fishery would lead to sub-optimal individual transferable quota management. Indeed, catch share institutions provide the rights to the harvest, but not the rights to resources. Under the catch share program, fishery managers decide and update the fishery-wide catch quota given the stock assessment, but they do not regulate the location of harvest or timing of harvest. Despite this weakness, individual transferable quota is still more efficient than catch quota or limited entry regimes. In this study, I consider the individual transferable quota regime as an example of rights-based management.

4.2 Model

The objective of this chapter is to show the evolution in fisheries management institutions. First, the study identifies and characterize three common fishery management institutions: open access, catch quota, and individual transferable quota. A model is constructed to characterize the three management institutions in terms of their relative efficiencies. For each institution, I determine a representative individual harvester's rent maximizing behavior and resulting fishery stock and effort. Then, the study presents a dynamic institutional evolution model with governance cost. I characterize the governance cost associated with each of the management institutions to examine possible institutional evolution scenarios.

Consider a representative fisherman. The total revenue gained by an individual fisherman i in time t can be expressed as the product of a fixed output price, p, and harvest, $x_{i,t}$,

$$\mathrm{TR}_{i,t} = px_{i,t}.$$

The total cost of fishing for a representative harvester i in time t can be expressed as a product of the unit cost of harvesting and the harvest. The unit harvesting cost is a function of the stock, S_t, and individual harvester's catchability, q_G, which can be interpreted as a percentage of the stock. The individual harvester's catchability, q_G, depends on the management regime that an individual operates in. In other words, an individual needs

to adjust his catchability given the institutional setting. In a sense, individual fishermen respond to different management regimes by adjusting their catchability, which results in a change in his unit harvesting cost. The unit harvesting cost, hence, can be expressed as $c(S_t, q_G)$. An index, G, denotes a management regime that an individual operates under. The total harvesting cost is, therefore,

$$\mathrm{TC}_{i,t} = c(S_t, q_G)x_{i,t}.$$

Further, let us suppose that the unit harvesting cost takes the form such that

$$c(S_t, q_G) = \frac{\theta}{S_t q_G},$$

where θ is a positive constant. This unit harvesting cost is a standard form used in previous fisheries economic literature (Clark, 2006). The unit harvesting cost function reflects that the cost decreases as stock and catchability increase. If the stock level is higher, the unit harvesting cost is lower. If the catchability is higher, the unit harvesting cost is lower.

Open Access

Let us first define the harvesters' behavior under an open access regime. Under open access, each individual harvester maximizes his profit at time t by solving

$$\max_{x_{i,t}} \pi_{i,t} = px_{i,t} - c(S_t, q_G)x_{i,t}.$$

By solving this problem, we have

$$c(S_t, q_G) = p. \tag{4.1}$$

Equation (4.1) shows the key implication of open access resource harvesting. That is, if there is no restriction on fishing activities, resource harvesters harvest until the rent is completely dissipated. From the unit cost function, this condition can be expressed as

$$\frac{\theta}{q_{OA} S_{\mathrm{OA}}} = p. \tag{4.2}$$

Catch Quota

Under a catch quota regime, also known as a total allowable catch regime, a fishery manager determines the maximum harvest level (i.e. catch quota) for each season. Once the total harvest reaches the predetermined maximum, the fishery is closed for the season. Each

individual resource harvester i maximizes his profit at time t by solving

$$\max_{x_{i,t}} \pi_{i,t} = px_{i,t} - c(S_t, q_G)x_{i,t}.$$

By taking the first order condition with respect to x_t,

$$c(S_t, q_G) = p.$$

From the unit harvest cost function at the fishery level, we have

$$\frac{\theta}{S_{CQ}q_{\mathrm{CQ}}} = p. \tag{4.3}$$

Compared to open access, the equilibrium stock is higher under a catch quota regime because of the harvest constraint. Hence, individual catchability under the catch quota regime, q_{CQ}, is higher than it is under the open access regime, q_{OA}.

Individual Transferable Quota

Under the individual transferable quota regime, individual harvesters are given shares of the total allowable catch for the season as individual quotas, Q_i. Individual quotas are allocated prior to the fishing season and are transferable; individual harvesters are allowed to either fulfill their quotas by harvesting by themselves or by selling their shares to others. They may also choose to purchase more shares from others. Each individual resource harvester maximizes his profit at time t by solving

$$\max_{x_{i,t}} \pi_{i,t} = px_{i,t} - c(S_t, q_G)x_{i,t}$$
$$\text{subject to } x_{i,t} \leq Q_{i,t}.$$

When the equality holds for the constraint, we can transform the problem in

$$\max_{Q_{i,t}} Q_{i,t}\pi_{i,t} = pQ_{i,t} - c(S_t, q_G)Q_{i,t}.$$

Clark (1990) points out that the right hand side represents the total benefits from the quota. Hence, by taking the derivative with respect to $Q_{i,t}$, we can obtain the marginal quota benefit as

$$\mathrm{MB}_{Quota} = p - c(S_t, q_G) = p - \frac{\theta}{q_G S_t}.$$

By denoting equilibrium quota price as m, the marginal benefit from obtaining the quota is $m - \text{MB}_{Quota}$. For a representative fisherman, we have

$$m_t = p - \frac{\theta}{S_t q_{\text{ITQ}}}, \tag{4.4}$$

where q_{ITQ} is the catchability in an individual transferable quota fishery. As Clark (1990) shows, if a quota market exists, a harvester buys more quotas when his marginal quota benefit exceeds the quota price, and vice versa. At the equilibrium, the quota price would be equal to the marginal benefit of the quota. From the unit harvesting cost function and considering a representative resource harvester, we have

$$\frac{\theta}{S_{ITQ} q_{\text{ITQ}}} = p - m. \tag{4.5}$$

From this condition, we find that, by assuming that the target stock level under the catch quota and individual transferable quota regimes are the same, individual catchability under the ITQ, q_{ITQ}, is greater under the individual transferable quota regime compared to the catch quota regime.

4.2.1 General Model of Scarcity Induced Institutional Change

Roumasset and Tarui (2013) formalize a model of resource management institutional change discussed by Demsetz (1967) and Anderson and Hill (1975). These two papers discuss that resource management institutions are introduced when the benefits from adopting resource governance outweighs the cost. Roumasset and Tarui (2013) present a model where resource governing institutional change is induced by resource scarcity. The idea is that as the resource gets scarce, the benefits from adopting resource governance increase. At a certain level of resource stock, the benefits of adopting a resource governance institution outweighs the cost of governance, and at this level, it is optimal to adopt a resource governance institution.

One of the major contributions of Roumasset and Tarui (2013) is the characterization of resource governance cost as a function of resource conservation. In the paper, Roumasset and Tarui define governance cost as a sum of one-time institutional investment cost (i.e fixed cost) and a variable cost that is a linear function of resource stock conserved relative to the case of open access. By denoting fixed cost as C and variable cost as $g(x_{\text{OA}} - x_t)$, the present value of the the total governance cost is shown as

$$\text{Total Governance Cost} = e^{-\rho\tau} C + \int_{\tau}^{\infty} e^{-\rho t} g(x_{\text{OA}} - x_t) dt.$$

At time $t = \tau$, a governing institution is adopted, incurring the one-time fixed cost. From that time on, the governance incurs a variable cost for each time period.

Given the governance cost function and by supposing that the initial stock, S_0, is above the optimal steady state level, Roumasset and Tarui (2013) show that a benevolent social planner solves a resource management problem, which is the dynamic maximization problem that solves for harvest, x_t, and the timing of institutional change, τ

$$\begin{aligned}
\max_{x_t,\tau} \quad & \int_0^\tau e^{-\rho t}\{p - c(S_t)\}\bar{x}dt - e^{-\rho\tau}C + \int_\tau^\infty e^{-\rho t}[\{p - c(S_t)\}x_t - g(x_{\text{OA}} - x_t)]dt \\
\text{subject to} \quad & \dot{S}_t = \begin{cases} F(S_t) - \bar{x} & \text{for } 0 < t < \tau \\ F(S_t) - x_t & \text{for } t \geq \tau, \end{cases} \\
& S_0 \text{ given,} \\
\text{and} \quad & 0 \leq x_t \leq \bar{x} \text{ for all } t,
\end{aligned} \tag{4.6}$$

where $\bar{x}$ indicates the exogenously determined upper bound for the harvest.

The inherent assumption is that open access prevails without governance. If there is no resource governance, the present value of net benefits from the fishery can be expressed as

$$\Pi_{NG}(S_0) = \int_0^{\tau(S_0, S_{\text{OA}}, \bar{x})} e^{-\rho t}\{p - c(S_t)\}\bar{x}dt. \tag{4.7}$$

This indicates that the fishery yields positive benefits until the stock reaches the steady state at time $t = \tau(S_0, S_{\text{OA}}, \bar{x})$. This is because a fishery harvests the upper bound of the harvest, $x_t = \bar{x}$, before it reaches the steady state. The time that the fishery reaches the steady state, $\tau(S_0, S_{\text{OA}}, \bar{x})$, can be determined by integrating the resource constraint $\dot{S}_t = F(S_t) - \bar{x}$, so that

$$\tau(S_0, S_{\text{OA}}, \bar{x}) = \int_{S_0}^{S_{\text{OA}}} \frac{1}{F(\omega) - \bar{x}} d\omega.$$

The details of this calculation is explained in the Appendix. As described in the previous section and by Roumasset and Tarui (2013), the steady state open access stock, S_{OA}, can be derived by $p = c(S_{\text{OA}})$. In the following, we continue to assume that the initial stock is in the neighborhood of the carrying capacity.

Roumasset and Tarui (2013) examine two governance cost scenarios: when governance has zero fixed cost and when governance has positive fixed cost. If there is no fixed governance cost, governance is adopted when the stock level reaches the optimal steady state, S^*. In other words, the institutional change happens at $\tau(S_0, S^*, \bar{x})$. Once the institutional change

happens, harvest drops from $\bar{x}$ to the optimal harvest, x^*. This can be expressed as

$$\Pi_{\text{Gov (No Fixed Cost)}} = \int_0^{\tau(S_0,S^*,\bar{x})} e^{-\rho t}\{p - c(S_t)\}\bar{x}dt + e^{\rho\tau(S_0,S^*,\bar{x})}\frac{\{p - c(S^*)\}x^* - g(\bar{x} - x^*)}{\rho}. \tag{4.8}$$

The first term is the rent in the period before the fishery reaches the steady state. In this period, a fishery harvest $x_t = \bar{x}$. Because the institutional change happens when the stock reaches the steady state, the fishery would always be at the steady state in the post-institutional change period. The rent in this period is expressed in the second term.

If there is positive fixed cost, institutional change happens somewhere between $t = \tau(S_0, S^*, \bar{x})$ and $t = \tau(S_0, S_{\text{OA}}, \bar{x})$. That is, the timing of institutional change falls between the steady state stock levels under optimal management and open access. Supposing that the institutional change happens at time T within the time frame, $T \in [\tau(S_0, S^*, \bar{x}), \tau(S_0, S_{\text{OA}}, \bar{x}))$, the present value of net benefits with governance can be expressed as

$$\Pi_{\text{Gov w/ Fixed Cost}}(T) = \int_0^T e^{-\rho t}\{p - c(S_t)\}\bar{x}dt - e^{-\rho t}\big(C + \frac{g\bar{x}}{\rho}\big) + e^{-\rho(T+\tau(S_T,S^*,0))}\frac{\{p - c(S^*) + g\}x^*}{\rho}.$$

Again, the first term shows the period before the institutional change. In this period, the fishery harvests $x_t = \bar{x}$. Because the stock is below the second-best steady state level at the time of the institutional change, a fishery harvest nothing for a brief period of time while the stock recovers to the second-best steady state level. The rent is realized once the stock recovers to the second-best steady state level at $t = \tau(S_T, S^*, 0)$.

Now, because the optimal switching time, T^*, is in the range $t = [\tau(S_0, S^*, \bar{x}), \tau(S_0, S_{\text{OA}}, \bar{x})]$, Roumasset and Tarui (2013) show that the sufficient condition under which the adoption of governance is optimal as

$$C \leq \frac{\{p - c(S^*)\}F(S^*) - g\{\bar{x} - F(S^*)\}}{\rho} - e^{\rho\tau(S_0,S^*,\bar{x})}\int_{\tau(S_0,S^*,\bar{x})}^{\tau(S_0,S_{\text{OA}},0)} e^{-\rho t}\{p - c(S_t)\}\bar{x}dt. \tag{4.9}$$

This implies that there is a possibility that no governance is optimal for resource governance regimes with large fixed governance costs.

4.2.2 Institutional Evolution in Fisheries Management

Roumasset and Tarui (2013) present a general model of institutional change, where institutional change happens only once. In reality, institutional change could occur multiple times. What is more, it is possible that institutional change may take the form of evolution. That is, less costly but less efficient institutions may be adopted as an intermediate step before

the transition to more efficient but also more costly institutions. In the earlier section, I characterized a catch quota and an individual transferable quota regime. I showed that under the catch quota regime, a fishery continues to make no economic rent though its harvest is restricted. These two institutions may be adopted in sequential order.

By supposing that the open access regime prevails without any resource governance institution, there are four scenarios of fisheries institutional evolution we can consider. The four scenarios are:

No Governance: a fishery remain as open access (i.e. no governance) forever;

Catch Quota as Final Institution: a fishery management institution changes from open access to catch quota and stays at catch quota forever;

Indirect Transition to Individual Transferable Quota: a fishery management institution evolve first from open access to catch quota before evolving to individual transferable quota;

Direct Transition to Individual Transferable Quota: a fishery management institution changes directly from open access to individual transferable quota.

An implicit assumption is that governance costs are sufficiently high or the stock is initially sufficiently abundant that open access is optimal at the outset. We are also assuming that once a fishery transitions to a more intensive resource governance regime, the fishery does not move back to a less intensive regime.

According to the database compiled by the Environmental Defense Fund, over 35 countries have adopted some variation of catch share programs [1]. Among the countries, Iceland and New Zealand were the first to adopt individual transferable quota programs in their fisheries. Iceland first implemented individual transferable quotas in 1976, New Zealand implemented individual transferable quotas in 1986 (Bonzon, 2010; Newell et al., 2002; Stavins, 2010). Many others have adopted a catch quota regime and, for many cases, fisheries went from open access to individual transferable quota management via some form of regulated open access.

To examine institutional evolution scenarios for fisheries management, let us first characterize the governance costs associated with the catch quota and the individual transferable quota regime. Under a catch quota regime, a fishery manager needs to determine the target biomass stock level. Given this stock level, a manager determines a maximum harvest allowed, catch quota, in the fishery per season. The quota is set before the season starts

[1] http://www.edf.org/oceans/catch-shares-resources

and harvesting activities continue until the quota is reached. The key governance costs associated with catch quota, therefore, are the cost of determining a target biomass stock level and corresponding quota (information cost), and the cost of monitoring to tally up the landings at the port (monitoring cost). There is also an enforcement cost to make sure that all the landings are reported properly to the managers. Under individual transferable quota, in addition to these costs, a fishery needs to establish rules associated with allocation and post-allocation transactions of shares. Before the individual transferable quota regime can take place, the harvest share needs to be allocated among harvesters.

For simplicity, assume the following characterization of governance cost associated with a catch quota and an individual transferable quota regime:

Assumption 4.2.1. *A catch quota regime does not incur fixed governance cost.*

Assumption 4.2.2. *Individual transferable quota regime incurs fixed governance cost.*

Assumption 4.2.3. *Catch quota and individual transferable quota regimes have equal variable governance cost.*

Assumption 4.2.4. *Variable governance cost is a linear function of resource conservation relative to open access, as specified in Roumasset and Tarui (2013).*

Assumption 4.2.3 comes from the assumption that monitoring and enforcement costs under a catch quota and an individual transferable quota regime are equal. For both regimes, managers are required to tally up the harvest for each season to make sure that the harvest does not exceed the total allowable catch for the season.

We have already defined the individual unit harvesting cost to take the form $c(S_t, q_i) = \dfrac{\theta}{q_i S_t}$. For calculation clarity, let us denote the unit cost function to be $c(S_t, q_G) = b(S_t)n(q_G)$, where $b(S_t) = \dfrac{\theta}{S_t}$ and $n(q_G) = \dfrac{1}{q_G}$. A manager's optimization problem can be expressed as

$$\begin{aligned}
\max_{x_t,\tau,T} \quad & \int_0^{\tau} e^{-\rho t}\{p - b(S_t)n(q_G)\}x_{OA}dt + \int_{\tau}^{T} e^{-\rho t}[\{p - b(S_t)n(q_G)\}x_t - g(x_{\mathrm{OA}} - x_t)]dt \\
& - e^{-\rho T}C + \int_T^{\infty} e^{-\rho t}[\{p - b(S_t)n(q_G)\}x_t - g(x_{\mathrm{OA}} - x_t)]dt \\
\text{subject to} \quad & \dot{S}_t = \begin{cases} F(S_t) - x_{OA} & \text{for } 0 < t < \tau \\ F(S_t) - x_t & \text{for } t \geq \tau, \end{cases} \\
& S_0 \text{ given,} \\
\text{and} \quad & 0 \leq x_t \leq \bar{x} \text{ for all } t.
\end{aligned} \tag{4.10}$$

In the objective function, τ denotes the transition timing from open access to the catch quota regime, and T denotes the transition timing to the individual transferable quota regime. The first institutional evolution scenario (i.e. no governance) is when $\tau = \infty$. The second institutional evolution scenario (catch quota forever) is when $T = \infty$. The third institutional evolution scenario (indirect transition form open access to individual transferable quota) is when $\tau \neq T$. The fourth institutional evolution scenario (direct transition from open access to individual transferable quota) is when $\tau = T$.

To determine the institutional evolution in fisheries management, let us consider two alternative scenarios for the fixed governance cost associated with the individual transferable quota regime: when fixed governance cost is independent of past management experience and when fixed governance cost is dependent on past management experience. Specifically, I suppose that fixed governance cost is $C = I$ for the former case and $C = I(z)$, where z is the number of years that a fishery operates under some form of management for the latter case. I examine the four institutional evolution scenarios for each of these two fixed governance cost specifications.

4.2.3 Fixed Governance Cost is Independent of Past Management Experience

No Governance By following Roumasset and Tarui (2013), let us suppose that open access fisheries prevail without governance. The present value of net benefits with no governance is described by equation (4.7) above (see also Roumasset and Tarui (2013)). This equation shows that the present value of net benefits from a fishery under open access occurs in the period before the fishery reaches the open access steady state. Before the stock reaches to the steady state, the fishery harvest is bounded exogenously at $\bar{x} > x_{OA}$, and the fishery is able to produce positive economic rent. Therefore, we can express the no governance scenario's present value of net benefits as

$$\Pi_{NG} = \int_0^{\tau(S_0, S_{OA}, \bar{x})} e^{-\rho t}\{p - b(S_t)n(q_{OA})\}\bar{x}dt. \tag{4.11}$$

Again, the steady state stock, S_{OA}, can be determined by $p = c(S_{OA})$. Once the steady state open access stock is determined, we are able to derive the time that the stock reaches the steady state by integrating the stock equation of motion as described in the Appendix.

Catch Quota as Final Institution If a management regime shifts from open access to catch quota, and it stays under catch quota forever, the present value of net benefits can be

expressed as

$$\Pi_{CQ} = \int_0^{\tau} \{p - b(S_t)n(q_{OA})\}\bar{x}dt + \int_{\tau}^{\infty} [\{p - b(S_t)n(q_{CQ})\}x_t - g(\bar{x} - x_t)]dt, \tag{4.12}$$

where τ indicates the optimal switching time to catch quota. The first term shows the gain from the period before catch quota is adopted. The second term shows the gain after catch quota is adopted. This scenario, however, turns out not to be feasible. Because the model assume perfectly elastic demand, the optimal harvesting path follows the most rapid approach path (Spence and Starrett, 1975). That is, it is optimal to harvest the maximum possible level, $\bar{x}$, until the stock reaches the steady state. With governance, by denoting the optimal steady state harvest as x^*, for a given initial stock level S_0, the time it takes for a fishery to reach the steady state can be specified. Denote the timing of the stock reaching the steady state as $\tau(S_0, S^*, \bar{x})$. At this point, a fishery has an option to introduce a catch quota regime. However, a catch quota regime fails to generate economic rent. This is from the condition $p = b(S_t)n(q_{CQ})$. At the steady state, a fishery manager chooses a quota level so that $Q^* = x^* = F(S^*)$, where $S^* > S_{\mathrm{OA}}$. This quota constraint, however, does not change the nature of harvesting behavior. Hence, individual harvesters face the condition $p = b(S^*)n(q_{CQ}) = \dfrac{\theta}{q_{CQ}S^*}$ as described in the previous section. At the fishery level, this indicates that the representative harvester's catchability coefficient, q, is higher under a catch quota regime compared to an open access regime. Therefore, the equation (4.12) will collapse to

$$\Pi_{CQ} = \int_0^{\tau(S_0,S^*,\bar{x})} e^{-\rho t}\{p - b(S_t)n(q_{OA})\}\bar{x}dt - e^{-\rho\tau(S_0,S^*,\bar{x})}\frac{g(\bar{x} - x^*)}{\rho}. \tag{4.13}$$

In sum, the transition to catch share at this point incurs negative economic rent due to governance cost. Hence, institutional change to catch quota as a final institution is not a feasible scenario.

Indirect Transition to Individual Transferable Quota While it is not feasible to switch to a catch quota regime as the final institution, there may be a role that a catch quota regime can play as a transitioning institution before the management switches to an individual transferable quota regime. The present value of net benefits when the fishery takes the indirect transition from open access to individual transferable quota via a catch

quota regime can be expressed as

$$\Pi_{\text{Indirect}} = \int_0^{\tau(S_0,S^*,\bar{x})} e^{-\rho t}\{p - b(S_t)n(q_{OA})\}\bar{x}dt - e^{-\rho\tau(S_0,S^*,\bar{x})}\frac{g(\bar{x}-x^*)}{\rho} \\ -e^{-\rho T}I + e^{-\rho T}\frac{\{p - b(S^*)n(q_{ITQ})\}x^*}{\rho}. \tag{4.14}$$

The first term is for the period when the fishery operates under open access. Because the transition happens before the stock reaches the open access steady state, the fishery harvest is at the maximum level at $\bar{x}$. Once the stock level reaches the optimal steady state harvest level, the manager impose a cap on harvest, or catch quota, for the fishery to stay at the optimal steady state stock. It is not until the regime switches to individual transferable quota, however, that the fishery is able to yield profit. By taking the partial derivative of equation (4.14) with respect to transition timing to individual transferable quota, T, we get

$$\frac{\partial \Pi_{\text{Indirect}}}{\partial T} = e^{-\rho T}[\rho I - \{p - b(S^*)n(q_{ITQ})\}x^*].$$

From this, we have

$$\frac{\partial \Pi_{\text{Indirect}}}{\partial T} > 0 \Leftrightarrow I > \frac{\{p - b(S^*)n(q_{ITQ})\}\bar{x}}{\rho},$$

and

$$\frac{\partial \Pi_{\text{Indirect}}}{\partial T} < 0 \Leftrightarrow I < \frac{\{p - b(S^*)n(q_{ITQ})\}\bar{x}}{\rho}.$$

These two conditions do not help us solve for the optimal switching timing to an individual transferable quota regime. Instead, these two equations give us the relationship between the fixed governance cost required to introduce an individual transferable quota and the benefits gained by the fishery without regard to variable governance cost. The above condition implies that it is optimal to delay the introduction of individual transferable quota forever if the fixed governance cost is greater than the discounted gains from the individual transferable quota regime. The second condition above implies that it is optimal to adopt an individual transferable quota early if the fixed governance cost is smaller than the discounted gains from the individual transferable quota regime.

Direct Transition to Individual Transferable Quota If the governance regime changes directly from open access to individual transferable quota at $t = T$,

$$\Pi_{\text{Direct}} = \int_0^T e^{-\rho t}\{p - b(S_t)n(q_{OA})\}\bar{x}dt - e^{-\rho T}\left(I + \frac{g\bar{x}}{\rho}\right) + e^{-\rho(T+\tau(S_T,S^*,0))}\frac{\{p - b(S^*)n(q_{ITQ}) + g\}x^*}{\rho}. \tag{4.15}$$

Again, the first term represents the period of open access. Because this case is analogous to the institutional change with fixed governance cost discussed in Roumasset and Tarui (2013), institutional change timing T is in the region $T \in [\tau(S_0, S^*, \bar{x}), \tau(S_0, S_{\text{OA}}, \bar{x}))$.

In order to find the optimal switching timing, take the partial derivative of equation (4.15) with respect to T,

$$\frac{\partial \Pi_{\text{Direct}}}{\partial T} = \rho e^{-\rho T} I + e^{-\rho T}\{p - b(S_t)n(q_{OA}) + g\}\bar{x} - e^{-\rho T + \tau(S_T, S^*, 0)}\{p - b(S^*)n(q_{ITQ}) + g\}x^*$$

The optimal transition timing can be determined by solving for T when $\dfrac{\partial \Pi_{\text{Direct}}}{\partial T} = 0$.

4.2.4 Fixed Governance Cost is Dependent on Past Management Experience

So far, we found that a catch quota regime cannot be the final institution and that an indirect transition case becomes equivalent to either no governance or a direct transition case unless $I = \dfrac{\{p - b(S^*)n(q_{ITQ})\}\bar{x}}{\rho}$. With the assumptions (4.2.1) through (4.2.4), the institutional evolution scenarios boil down to no governance and direct transition cases if the fixed governance cost is constant and independent of past management experience. Whichever of the no governance or the direct transition scenarios has the larger present value of net benefits is the efficient sequence.

Now, let us consider a possibility that institutional governance cost is dependent on management history. That is, the fixed governance cost associated with an individual transferable quota regime is influenced by past governance experience. As Libecap (2009) points out, one of the major obstructions to implementing individual transferable quotas stems from the difficulty in reaching agreements on how to allocate the shares. As a fishery gain management experience, may be able to learn to form an agreement more easily, thereby reducing cost of adopting individual transferable quota.

To state this notion of learning by managing more clearly, let us assume the following:

Assumption 4.2.5. *Fixed governance cost associated with the individual transferable quota regime is a function of the years that a fishery operated under some form of resource governance. Let z be the number of management years, then the fixed governance can be expressed as $I(z)$ where $I'(z) < 0$ and $I(0) \geq I$.*

Hence, the fixed governance cost of an individual transferable quota regime under indirect transition can be expressed as $z = T - \tau(S_0, S^*, \bar{x})$ and under direct transition as $z = 0$.

Further, let us suppose that $I(z) = \dfrac{I}{\delta + z}$, where $0 < \delta \leq 1$ is a positive constant to ensure that $I(0) \geq I$.

Because fixed governance cost is irrelevant for both the no governance scenario and the catch quota as the final institution scenario, the present value of net benefits under these two scenarios remain the same as in the case when fixed governance cost is independent of past management experience. The change in fixed governance cost composition, however, changes the present value of net benefits under the indirect transition and direct transition scenarios.

Indirect Transition to Individual Transferable Quota

For the indirect transition, the present value of net benefits can be expressed as

$$\begin{aligned}\Pi_{\text{Indirect}} = \arg\max_{\tau,T} \quad & \int_0^{\tau(S_0,S^*,\bar{x})} e^{-\rho t}\{p - b(S_t)n(q_{OA})\}\bar{x}dt - e^{-\rho\tau(S_0,S^*,\bar{x})}\frac{g(\bar{x}-x^*)}{\rho} \\ & -e^{-\rho T}\frac{I}{\delta + (T - \tau(S_0,S^*,\bar{x}))} + e^{-\rho T}\frac{\{p - b(S^*)n(q_{ITQ})\}x^*}{\rho}.\end{aligned} \tag{4.16}$$

The first term shows the period of open access, where the fishery harvests at the upper bound of the harvest, $\bar{x}$. Because catch quota does not incur a fixed cost, the transition to the catch quota happens when the stock reaches the second-best optimal level. Recall that we suppose that the variable governance cost under the catch quota and individual transferable quotas are the same. The second term represents the discounted variable governance cost. The third term represents the governance fixed cost associated with the individual transferable quota. The last term shows the rent under the individual transferable quota regime. Comparing this to equation (4.14), the change appears in the third term, where governance fixed cost is a function of $z = T - \tau(S_0, S^*, \bar{x})$.

In order to determine the optimal switching timing to the individual transferable quota, take the derivative of equation (4.17) with respect to T, and we have

$$\begin{aligned}\frac{\partial \Pi_{\text{Indirect}}}{\partial T} = \; & e^{-\rho t}\Big[I\Big(\frac{1}{(\delta + (T - \tau(S_0,S^*,\bar{x})))^2} + \frac{\rho}{\delta + (T - \tau(S_0,S^*,\bar{x}))}\Big) \\ & -\{p - b(S^*)n(q_{ITQ})\}x^*\Big].\end{aligned} \tag{4.17}$$

The optimal switching timing to individual transferable quota can be derived by setting this equal to 0, and therefore solving

$$I = \{p - b(S^*)n(q_{ITQ})\}x^*\Big(\frac{1}{(\delta + (T - \tau(S_0,S^*,\bar{x})))^2} + \frac{\rho}{\delta + (T - \tau(S_0,S^*,\bar{x}))}\Big)^{-1} \tag{4.18}$$

for T.

Direct Transition to Individual Transferable Quota

For the direct transition, we have

$$\Pi_{\text{Direct}} = \int_0^T e^{-\rho t}\{p - b(S_t)n(q_{OA})\}\bar{x}dt - e^{-\rho T}\left(\frac{I}{\delta} + \frac{g\bar{x}}{\rho}\right) + e^{-\rho(T+\tau(S_T,S^*,0))}\frac{\{p - b(S^*)n(q_{ITQ}) + g\}x^*}{\rho}. \tag{4.19}$$

The first term represents the period of open access. Because of the fixed governance, the transition to the individual transferable quota is in the region where $T \in [\tau(S_0, S^*, \bar{x}), \tau(S_0, S_{\text{OA}}, \bar{x}))$. Hence, the rent is realized when the stock recovers to the second-best steady state level at $t = \tau(S^T, S^*, 0)$ as described earlier. Comparing this to equation (4.15), the change appears in the second term.

In order to determine the optimal switching timing to the individual transferable quota, take the derivative with respect to T, and we have

$$\frac{\partial \Pi_{\text{Direct}}}{\partial T} = \rho e^{-\rho T}\frac{I}{\delta} + e^{-\rho T}\{p - b(S_t)n(q_{OA}) + g\}\bar{x} - e^{-\rho(T+\tau(S_T,S^*,0))}\{p - b(S^*)n(q_{ITQ}) + g\}x^*.$$

The optimal switching timing to individual transferable quota can be derived by solving

$$\frac{\rho I}{\delta} = e^{\rho\tau(S_T,S^*,0)}\{p - b(S^*)n(q_{ITQ}) + g\}x^* - \{p - b(S_t n(q_{OA}) + g\}\bar{x} \tag{4.20}$$

for T.

4.3 Which Institutional Evolution Scenario is Optimal?

Optimal institutional evolution scenarios can be determined by comparing the present value of net benefits for each of the institutional evolution scenarios. This can be summarized as

$$\max\{\Pi_{\text{NG}}, \Pi_{\text{CQ}}, \Pi_{\text{Indirect}}, \Pi_{\text{Direct}}\}.$$

Note that $\Pi_{\text{NG}}, \Pi_{\text{CQ}}, \Pi_{\text{Indirect}}$, and Π_{Direct} reflect the optimal switching timing to the relevant management institutions. In other words, they are the maximum present value of net benefits that each institutional evolution scenario can take.

So far, we have examined each of the scenarios under two alternative fixed governance cost scenarios. If fixed governance cost is constant and is independent of past management experience, we found that optimal institutional scenarios are reduced to either a no gover-

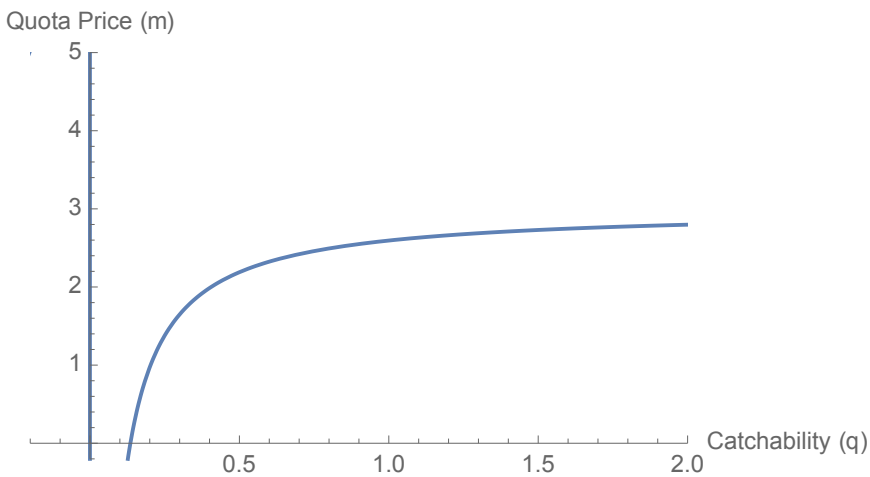


Figure 4.1: Relationship between Catch-ability Coefficient and Quota Price

nance scenario or a direct transition scenario. If fixed governance cost is a function of past management experience, then we have no governance, indirect transition, and direct transition as candidates for optimal institutional evolution scenarios. To illustrate cases when direct transition is optimal and when indirect transition is optimal, let us assume parameters and constants to take the values of $\rho = 0.02, p = 2, \theta = 3, \gamma = -.5, \kappa = 10, g = 1, I = 2$.

We also assume that $q_{\text{OA}} = q_{\text{ITQ}} = 0.4$. q_{CQ} can be analytically solved as 0.2. The reason that q_{ITQ} cannot be solved analytically comes from the fact that the catch-ability factor under an individual transferable quota depends on the price of the catch quota. Figure 4.1 shows a positive relationship between a catch-ability factor in a fishery under an individual transferable quota regime and the quota price. This implies that higher a quota price corresponds to higher catch capacity among the vessels in the fishery.

In the following, let us examine two examples with fixed governance cost as a function of past management experience (i.e. $C = \dfrac{I}{\delta z}$, where z is the number of years in management). In the first example, we assume that $\delta = 0.5$. In the second example, we assume that $\delta = 0.1$. The interpretation of the difference between the two parameter assumptions is that the latter case results in higher fixed governance cost especially if the fishery does not have any previous management experience. In other words, a fishery face higher fixed governance cost if the fishery switches to an individual transferable quota regime directly from no governance compared to the indirect transition scenario.

4.3.1 Example 1: Direct Transition is Optimal

Figure 4.2 shows the stock paths under no governance, direct transition, and indirect transition scenarios. No governance scenario is shown by the thin black line. The indirect

transition scenario is shown by the blue dotted line. The direct transition scenario is shown by the solid red line.

With no governance, stock continues to decline until the stock reaches the open access steady state value of $S_{OA} = 3.75$ at $t = \tau(S_0, S_{OA}, \bar{x}) = 14.85$. Under the indirect transition scenario, the stock continues to decline until the stock reaches the optimal steady state value of $S^* = 7.4$ at $t = \tau(S_0, S^*, \bar{x}) = 2.95$. At this time, management switches from open access to the catch quota regime. Catch quota continues until it switches to an individual transferable quota regime at $t = 3.92$. This is the optimal switching timing to the individual transferable quota, and is derived by solving equation (4.18). Under the direct transition scenario, the stock continues to decline further down below the optimal steady state. Transition to an individual transferable quota regime happens at $t = 10.93$, when the stock level is at $S_T = 4.84$. This optimal switching timing to an individual transferable quota regime is derived by solving equation (4.20). At this point, because the stock is below the optimal steady state level, the fishery does not harvest anything until the stock recovers to the level of optimal steady state at $t = T + \tau(S_T, S^*, 0) = 13.15$.

Figure 4.3 shows the corresponding dynamic harvest paths. With no governance, the fishery continue to harvest $\bar{x} = 1.5$ until the stock reaches the steady state. Again, this is because the harvest is bounded at $x_t = [0, \bar{x}]$, where we assume that the upper bound is $\bar{x} = 1.5$ for the purpose of numerical illustration. At the steady state, with no governance, the fishery harvest $x_{OA} = 1.17$. Under the indirect transition, the fishery continues to harvest $\bar{x} = 1.5$ until the stock reaches the optimal steady state. When the stock is at the steady state, the manager impose catch quota of $Q^* = x^* = 0.96$. Under the direct transition, the fishery continues to harvest $\bar{x} = 1.5$ until $t = 10.93$. At this point, the fishery manager impose a fishing moratorium until the stock recovers. The stock recovers to the steady state level at $t = T = \tau(S_T, S^*, 0) = 1.15$. At this point, the fishery resumes harvesting with an individual transferable quota with the harvest limit of $x_t = x^* = 0.96$.

In this example, we find that direct transition yields the highest present value of net benefits of $\Pi_{Dir} = 22.32$, followed by indirect transition's $\Pi_{Ind} = 22.02$. The no governance yields the present value of net benefits of $\Pi_{NG} = 13.54$. Hence, direct transition is the optimal institutional evolution path in this example.

4.3.2 Example 2: Indirect Transition is Optimal

Figure 4.4 shows the dynamic stock paths and Figure 4.5 shows the corresponding dynamic harvest paths. The no governance scenario is shown by the thin black line. The indirect transition scenario is shown by the blue solid line. The direct transition scenario is shown

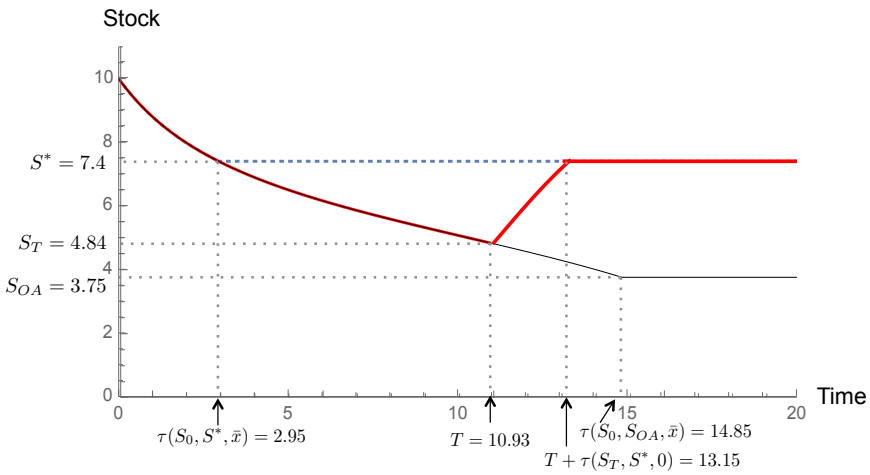


Figure 4.2: Stock Path (Direct Transition is Optimal)

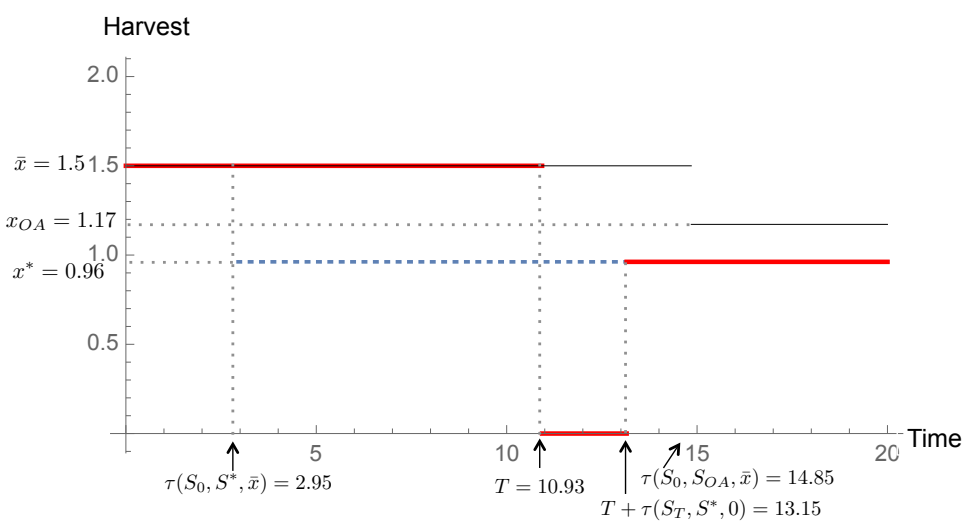


Figure 4.3: Harvest Paths (Direct Transition is Optimal)

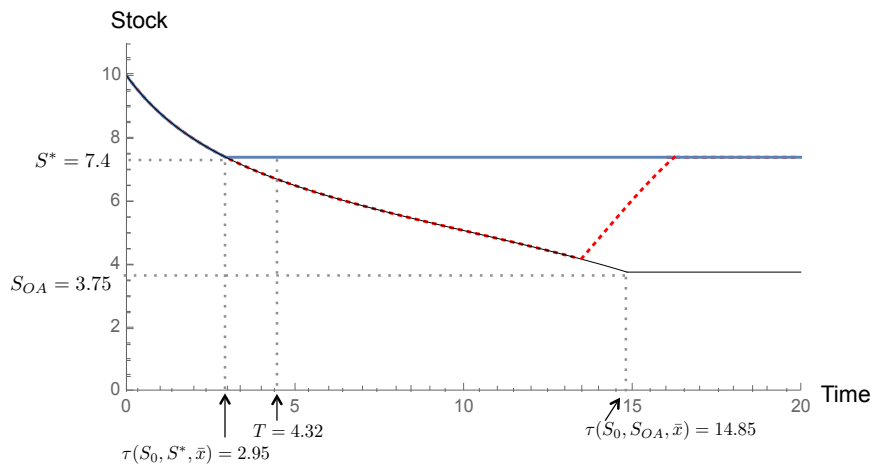


Figure 4.4: Stock Path (Indirect Transition is Optimal)

by the red dotted line.

In this example, indirect transition yields the present value of net benefits of $\Pi_{Ind} = 21.68$, followed by no governance's $\Pi_{NG} = 13.54$. Direct transition yields the lower present value of net benefits than the no governance case at $\Pi_{Dir} = 9.88$.

The no governance scenario in this example follows exactly the same paths as the earlier example described in Figure 1 and 2. For indirect and direct transition scenarios too, overall transition paths follow the same logic as the earlier examples. However, because governance cost is set so that no previous management results in relatively higher fixed governance cost under the direct transition scenario, optimal switching timings to individual transferable quota under both indirect and direct transition scenarios differ from the earlier example.

Under the indirect transition, the management switches to the catch quota regime at $t = \tau(S_0, S^*, \bar{x}) = 2.95$. The management then switches to an individual transferable quota regime at $t = 4.32$. Under the direct transition scenario, due to high fixed governance cost, the optimal switching timing is delayed until $t = 13.33$ compared to the earlier example. This results in the fishery closing for a longer time period because the stock is depleted more than in the earlier example. In summary, indirect transition is found to be the optimal institutional evolution path in this example.

4.4 Conclusion and Discussion

This study aims to solve the puzzle that many fisheries operate under an open access or a regulated open access regime despite the previous studies pointing out their inefficiencies. To do so, the study first identifies and characterizes three key fishery management institutions: open access, catch quota, and an individual transferable quota regime. This study offers an

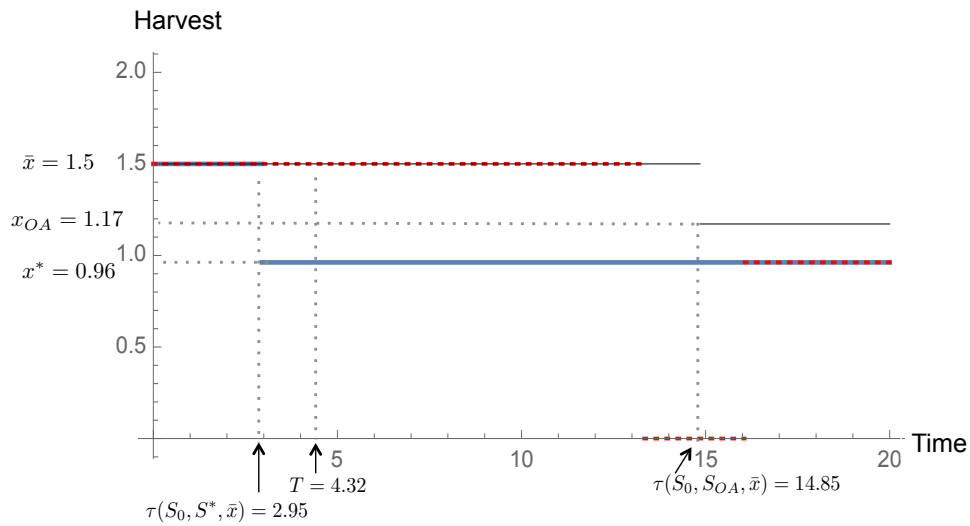


Figure 4.5: Harvest Paths (Indirect Transition is Optimal)

answer to the puzzle by investigating institutional evolution scenarios where an open access fishery evolves to rights-based management. Specifically, we show how resource governance may evolve over time by considering four institutional evolution scenarios: 1) there is no governance (i.e. open access), 2) governance goes from open access to regulated open access, and stays at regulated open access forever, 3) governance shifts indirectly from open access to rights-based management via regulated open access, and 4) governance shifts directly from open access to rights-based management.

There are three key findings. First, the second institutional evolution scenario, which examines the transition from open access to regulated open access, specifically, a catch quota regime in the example examined in this study, as the final institution is not feasible. This comes from the fact that regulated open access leads to a steady state condition such that the institution fails to produce economic rent. What is more, with positive governance cost, a catch quota regime yields negative economic rent at the steady state. Therefore, the no governance case would outperform this scenario.

Second, with a constant fixed governance cost, the institutional evolution options reduce to no governance or direct transition. This can be shown by looking at the relationship between the present value of net benefits and optimal switching time to an individual transferable quota regime under indirect transition. Under the indirect transition, we find that if the fixed governance cost is smaller than the steady state net benefits aside from the variable governance cost divided by the discount rate, it is optimal to switch as early as possible. If the fixed governance cost is greater, then the switch to individual transferable quota is postponed forever.

Third, if the fixed governance cost depends on the fishery's past management experience, indirect transition, direct transition, and no governance scenarios all remain as optimal institutional evolution options. The study showed examples of indirect and direct transition being the optimal institutional evolution paths respectively by using numerical illustrations. The numerical illustration highlights that the size of fixed governance cost as the key determinants of optimal institutional evolution. In the examples presented, higher relative fixed governance cost under direct transition compared to indirect transition resulted in the indirect transition scenario being the optimal institutional evolution path.

In reality, different fisheries have different magnitudes of fixed governance cost. Findings from this study suggest that this could be the source of heterogeneity among management practices that take place in the fisheries around the world. The results indicate that fixed governance cost determines the duration of regulated open access before the regime switches to a rights-based management. If the fixed cost is relatively small, the regime would switch from open access to a rights-based management directly.

Another important implication of this study is that sub-optimal management such as catch quota could be an important step towards more efficient rights-based management. While catch quota does not generate economic rent, it could add to a fishery's management experience, which could reduce the fixed cost associated with developing individual transferable quota. In addition, catch quota forces a fishery to maintain optimal steady state level of stock. In other words, while optimal direct transition from open access to individual transferable quota requires a period of stock recovery that requires fishing moratorium, indirect transition allows resource harvesters to harvest at the steady rate without moratorium. In reality, many years of fishing moratorium impacts fishermen's welfare significantly, and avoiding moratorium may be very beneficial.

As Libecap (2007b) points out, rights-based management may be delayed if the fishermen are not able to agree on how to allocate the shares among themselves. This agreement cost is an important fixed cost component. If a fishery's experience in regulated open access could reduce the agreement cost, the fishery may benefit from taking the indirect route to rights based management via regulated open access.

In this study, individual cathcablity depends on the management institution that an individual operate under. Individual catchability is not endogenously determined in the current setting. Future research should investigate how individuals respond to different management regimes endogenously. For such study, one would relax the assumption on homogeneous fishermen. In reality, different fishermen have different levels of skill. Hence, the response to different management regimes would vary from fisherman to fisherman. This area of research, that is the fishery management with heterogeneous fishermen, is relatively

new but is promising. Hence, I will provide a brief discussion on this topic in the conclusion to this dissertation.

Appendix: Calculation of the Transition Timing

Transition timing can be determined by the equation of motion, $\dot{S}_t = F(S_t) - x_t$, and set of initial stock level, stock level at the time of switching, and constant harvest. Because the price is fixed, the harvest path is bang-bang. For stock levels that are above the steady state, it is optimal to harvest maximum level $x_t = \bar{x}$ (Spence and Starrett, 1975). For stock levels that are below the steady state, it is optimal to harvest nothing (i.e. $x_t = 0$).

Hence, by denoting the stock level at the switching time as S_τ, and constant harvest level as x, from the equation of motion,

$$\dot{S}_t = \frac{dS}{dt} = F(S_t) - x.$$

Taking the integral of both sides,

$$\int_{S_0}^{S_\tau} dt = \int_{S_0}^{S_\tau} \frac{dS}{F(S) - x},$$

switching time can be obtained from

$$\tau(S_0, S_\tau, x) = \int_{S_0}^{S_\tau} \frac{dS}{F(S) - x}.$$

Chapter 5

Conclusion

5.1 Summary

This dissertation investigates contemporary challenges and promising remedies regarding fishery management: aquaculture production, trans-boundary fish movements, and the transition from open access to rights-based management.

Chapter 2 investigates the impacts of aquaculture production on fishery management. This is motivated by the increase in aquaculture production that has taken place since the 1980s, as capture fishery production continues to suffer from stock depletion. Because aquaculture and capture fishery production interact in the market, we need a framework to examine them together. I develop a framework by following the framework of a backstop model, which was initially used to understand the optimal extraction behavior of exhaustible resources such as oil. By following the study by Krulce et al. (1997), which applies the model to the case of a renewable resource, a groundwater aquifer with desalination as a backstop, I develop a model to study open access and optimally managed fisheries with aquaculture as a backstop. The model shows a costly substitute technology, such as aquaculture, may be used once wild stocks are depleted to the point where harvesting of the wild resource is too costly. A backstop can only be viable if the steady state price of fish is higher than the cost of the backstop. If the net price with a backstop is greater than without a backstop, I find that aquaculture production contributes to conserving more wild stock in the steady state while keeping the price constant. Aquaculture supplies a close or identical substitute for wild caught fish; understanding the interaction of aquaculture and capture fisheries is important for better management of capture fisheries. This implies that commercial fishery managers need to take production from aquaculture into consideration, because the optimal harvest path is altered by the existence of aquaculture production.

Chapter 3 develops a model for the management of trans-boundary fish stocks. While

previous studies on straddling and highly migratory stocks have focused on seasonal migration, this study focuses on non-seasonal movements of fish in and out of countries' exclusive economic zones. In addition, I take the leakages of stocks to international waters into consideration. This model is especially relevant in studying the management of tropical tuna fisheries in the Western and Central Pacific. One of the most commercially important tunas is Skipjack tuna, and their movements are dictated by the availability of feed. Thus, a model of the non-seasonal movements of fish is relevant. In addition, Pacific island countries' exclusive economic zones are surrounded by international waters, and hence, consideration of the leakages of stocks to international waters is important. Using numerical illustration, I present the benefit from cooperation as compared to a non-cooperative management regime. The study shows that cooperation is beneficial when there is fish migration. The numerical illustration shows that side payments may facilitate the negotiation to reach the Nash bargaining solution when two countries have different migration rates; The country with a higher migration rate would make a side payment to the other since the country with a higher rate gains more from the cooperation than the other. Motivated by the situation in the tropical tuna fisheries in the Western and Central Pacific, where Pacific island countries sell fishing access rights to distant water fishing vessels, the study extends the numerical illustration and shows that the countries are able to achieve optimal management by setting the fishing license fees equal to the product of daily catch and net price.

Chapter 4 develops a model of fisheries management institutional evolution to investigate the puzzling reality that many fisheries operate under sub-optimal management institutions despite previous studies' recommendations to transition to more efficient rights-based management regimes. To investigate under what conditions institutional change happens, I identify three common types of fishery management institutions: open access, catch quota, and individual transferable quota. First, I characterize the three management institutions in terms of their relative efficiency. Then, I investigate institutional evolution scenarios where a fishery transitions from an open access to an individual transferable quota regime. For each of the scenarios, I consider two assumptions: one where fixed governance cost is independent of past management experience and one where fixed governance cost is dependent on past management experience. The latter scenario takes learning by managing into consideration. By assuming that individual skills are equal across agents, a transition from open access to catch quota as the final institution is not feasible because the catch quota regime fails to generate economic rent. However, when there is learning by managing, catch quota may be used as an intermediary institution along the path to an individual transferable quota regime. In effect, learning lowers fixed cost of governance and makes a transition to individual transferable quota possible.

5.2 Future Research Direction

The chapter on institutional evolution suggests that both open access and catch quota lead to complete rent dissipation, hence a catch quota regime can only be used as an intermediary institution. This, however, is contingent on the assumption that fishermen have equal skills. In reality, fishermen are likely to have varying degrees of skill. For example, some fishermen are better at finding a location where fish congregate. Some may be better at retaining a more productive crew. When fishermen are heterogeneous, open access and catch quota may generate rent.

In recent years, fisheries economics literature has started focusing on the importance of fishermen heterogeneity. There are several sources of the heterogeneity. Namely, individual skill and risk preference are considered the main sources of the heterogeneity. Aside from the fisheries economics literature, in the field of international trade, Melitz (2003) develops a model that shows the firm's entry and exit decision into an export market where firms have different heterogeneous productivity. Taylor (2011), which investigates the impacts of international trade on North American bison hunting, considers heterogeneous hunting skills as well.

The framework presented in these two papers can be adopted to develop a model to characterize fisheries management with heterogeneous fishermen. For example, to characterize the open access, catch quota, and individual transferable quota regimes, consider individual-level decision making. Each individual fisherman decides how much effort to input to harvest fish. Each individual also determines whether to stay or exit the fishery. In order to stay in the fishery, a fisherman must at least break-even. Hence, a marginal fisherman break even while others earn inframarginal rents, even under the open access.

Given the individual decisions, a manager maximizes the total present value of net benefits of the fishery. Under the catch quota and individual transferable quota regimes, a fishery manager chooses the number of harvests. If a manager knows the distribution of individual skills of potential fishermen in the fishery, a manager is able to set the optimal quota that would determine the skill level of a marginal fisherman. In summary, when individuals have different skills, the open access and catch quota regime yield positive economic rent. Future studies should investigate how individual heterogeneity would affect the rents under different institutional settings.

In this dissertation, I developed dynamic bioeconomic models to investigate contemporary fishery management issues. While the models developed in this dissertation are useful for understanding some big picture problems, the next step in this research agenda is to refine these models so that they can be directly applied to real world fishery management.

For example, the model of trans-boundary fish management developed in Chapter 3 can be extended in two different ways. First, I can extend the two-country model to a more general N-country model. The model becomes more beneficial if it can be used to simulate the actual situation in the Western and Central Pacific, where countries with the largest tuna stocks cooperate while others do not.

Second, it would be worthwhile to extend the model to incorporate the behaviors of distant water fishing fleets. Currently, the model only focuses on the coastal states behaviors to manage their stocks. However, depending on their management decisions, distant water fishing fleets may alter their strategy for when, where, and how much to harvest. For example, when the coastal states enter into a cooperation and restrict the harvest amount, some distant water fishing vessels may exit the market. This is a promising area of economic research as more economists are applying a game theory approach that is similar to the one used in Chapter 3 to study trans-boundary fish resources. For example, (Bailey et al., 2013) examines the interaction among vessels with different gear types in the Pacific tuna fishery.

Another promising area of research, following this dissertation, would be to study cooperatives. Chapter 4 focused on the transition in management regimes from open access to individual transferable quota. As Costello and Deacon (2007) point out, cooperatives may be able to regulate fishing efforts better than an individual transferable quota program. While individual transferable quotas are used dominantly in countries such as New Zealand and Iceland, cooperatives are more common in countries like Japan. It would be interesting to investigate the efficiency difference between individual transferable quota programs and cooperatives. In addition, it would be interesting to investigate why some fisheries choose individual transferable quota and others choose cooperatives.

Finally, aquaculture is often neglected from fisheries management studies. Aquaculture production continues to increase, and it plays an increasingly large role in the global seafood market. While Chapter 2 studies both ends of the management spectrum, open access and first-best optimal, many fisheries lie between the two. The next step in this research agenda would be to investigate the impacts of increased aquaculture production on fisheries that operate under regulated open access. Valderrama and Anderson (2010) show a price decrease due to increased aquaculture production results in decreased effort inputs in a regulated open access fishery. It would be interesting to investigate whether a price decline due to increased aquaculture production would have the same effects on fisheries that operate under an individual transferable quota regime.

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