Heterogeneous Agents and Mechanism Design in Cooperative Resource Management

Licensing Considerations for a Tuna Coalition in the Pacific Ocean

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This work is dedicated to my family, especially to my mum and dad. This journey would not have been possible without your love, encouragement and support.

To my sister Fe, we miss you dearly. Rest in love.

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Abstract

The Pacific Ocean contributes more than 50 percent to global tuna production. The central and eastern regions have the most productive tuna fisheries in the Pacific. These regions include countries that are signatories to the Parties to the Nauru Agreement (PNA), a coalition of eight countries rich in tuna resources.

In 2007 the PNA introduced the Vessel Day Scheme (VDS), an effort or input based management scheme. Under the VDS, licenses to fish in PNA exclusive economic zones (EEZ) are sold on a 'per-day effort' basis. Each member country is assigned a share of the licenses which are specific to each country. Each country is responsible for the sale of its licenses, the majority of which are sold by auction to foreign fishing fleets. A key aim of the PNA countries is to ensure the future health of the fishery, while maximizing the returns from this important source of income. This thesis attempts to contribute to this effort by examining the PNA and the VDS to analyse two key questions.

The first question is whether the PNA should switch from the VDS to an output based regulation scheme, where licenses are sold based on the catch size. As an effort based scheme, the VDS has only indirect control of the landed catch size of each vessel, and a key criticism is that there is no upper limit on the size of the catch. Not only could the catch value be higher than the license revenue, this has also led to concerns about the sustainability of the fishery. The second question is whether a single global license allowing access to all countries would have any significant benefits over the current licenses which are specific to each country. Basic economic theory suggests that selling licenses individually yields lower revenue levels, relative to selling licenses as a coalition. However, a key consideration is a sharing rule that would be used to distribute revenue shares from a single license. An independent review of the VDS in 2014 recommended these two issues, among others, for further analysis. I address these questions in three steps.

First, I introduce heterogeneity of fishing vessels into the standard textbook model for a single fishery and show that in this single country case, revenue from output regulation is always higher relative to input regulation. Although this result is important, it provides limited insight into a multi-country setting such as the PNA, which has additional dynamics between countries. Second, extending this model to a two country case the analysis suggests that under ideal conditions, output regulation still yields higher income levels. However, in this multi-country setting each fishing vessel has to choose which country to buy licenses from. This additional dynamic reveals that without the assumption of perfect information for the fishery manager, achieving the target harvest and stock levels set by the manager can be difficult.

Finally, I compare the returns from selling a single global license relative to individual local licenses by developing a revenue sharing mechanism based on the distribution of fish stocks over each member country. The results show that a single license not only yields greater revenue levels, but also provides a more stable revenue stream over time.

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Chapter 1

Introduction

The Pacific Ocean contributes more than 50 percent to global tuna production (FAO 2010). The central and eastern regions have the most productive tuna fisheries in the Pacific. These regions include countries that are signatories to the Parties to the Nauru Agreement (PNA), a coalition of eight Pacific Island Countries (PICs) known to be rich in tuna (Aqorau 2009). The returns from these fisheries represent a significant source of income for the PNA members. In 2007 the PNA introduced the Vessel Day Scheme (VDS), an effort or input based management scheme. Under the VDS, licenses to fish in PNA exclusive economic zones (EEZ) are sold on a 'per-day effort' basis. A license gives fishing vessels the right to fish for one day. As a coalition the PNA sets the total allowable catch (TAC) to be harvested in their combined EEZ. An estimated total allowable effort (TAE) level is then determined which would yield the TAC. The TAE determines the total number of fishing days in a season. Each member country is assigned a share of the TAE, to be sold as licenses which only allows access to the seller's EEZ. Due to the increased bargaining power of the coalition, the VDS significantly increased the returns of fishing revenues to the PNA members.

As an effort based scheme, the VDS has only indirect control of the landed catch size of each vessel. The key criticism of the VDS is that there is no upper limit on the size of the catch. As the catch value is potentially higher than the value of the returns from the sale of licenses, revenue levels may not be maximized. In addition, the number of total allocated catch days, and total catch tonnage have steadily increased since the implementation of the VDS. This has led to concerns that the PNA fishery may be potentially over-fished in the near future if this trend continues. As a result, proposals have been made for a move to the relatively more established output based management scheme, where licenses are sold per unit of harvest. Under such an arrangement, fishing vessels pay for the right to catch a certain quantity of fish, most likely measured in tonnage.

A key aim of the PNA countries is to ensure the future health of the fishery, while maximizing the returns from this important source of income. This thesis attempts to contribute to this effort by examining the PNA and the VDS to develop models tailored specifically at examining two key questions. The first question is whether the PNA should switch from the VDS to an output based regulation scheme. The second question is whether a single global license allowing access to all countries would be preferred over the current licenses which are specific to each country. An independent review of the VDS was conducted by Anarson (2014) at the request of the PNA. The review was comprehensive and made several recommendations related to governance, design, as well as legal aspects of the VDS. Among these were recommendations that research be conducted on the two issues which form the core research questions of this thesis.

The first question was brought to the forefront of the policy agenda in the Pacific Island community, particularly in the last five years primarily due to concerns about overfishing. The proponents of a quota based scheme highlighted its success in other countries, and suggest that this would carry over to the PNA case. There are two problems with this point of view. Firstly, as far as the author is aware, specific comparisons between input and output regulation have not been made in the fisheries economics literature. One of the reasons for this is that the current models considered as standard in the field, cannot distinguish between the two management schemes as the outcomes are identical. Secondly, the experiences of output regulation in other fisheries may not be relevant in the PNA context. The PNA as an institution is unique, and the mechanisms that it employs to manage the fishery draws together many different aspects of economics which are complex in their own right. Cooperative management of a fishery at the scale or complexity of the PNA has not been attempted anywhere else in the world. A key consideration for a switch to harvest based licenses is how well the PNA will be able to monitor harvest levels. For these reasons it may be a mistake to suggest that success in other fisheries will carry over to the PNA, without considering the unique circumstances and context of the PNA.

The second question asks whether a single license for the entire coalition could be a superior approach to license sales, as compared the current practice of members selling country specific licenses. Regionalism is a key component of the development agenda for the Pacific Islands region as a whole, and the PNA is a prime example of this approach. Although a single license for the PNA is not a topic that is currently visible within the policy agenda of the PNA, consideration of such a mechanism would add value to the overarching theme of regionalism. Basic economic theory suggests that the advantages from selling a single licenses relative to competing as sellers could be significant. A single license would allow the PNA to act as a monopoly, raising prices to extract as much profit from the fishery as possible. However, characterizing these advantages as well as a mechanism to share the revenue among members of the PNA is not a trivial exercise.

Given the scale and complexity of the PNA, it is necessary to address these issues in smaller more manageable steps, with added assumptions to further simplify and focus the analysis on the core issues under consideration.

First I provide a background of the PNA and the VDS in Chapter 2. In Chapter 3 I introduce heterogeneity of fishing vessels into the standard textbook model for a single fishery and show that in this single country case, revenue from output regulation is always higher relative to input regulation. Although this result is important, it provides limited insight into a multi-country setting such as the PNA, which has additional dynamics between countries. In Chapter 4, I extend this model to a two country case which is a simplification of the eight-country PNA case. The results from this analysis suggests that under ideal conditions, output regulation is still predicted to yield higher income levels. However, in this multi-country setting each fishing vessel has to choose which country to buy licenses from. This additional dynamic reveals that without the assumption of perfect information for the fishery manager, achieving the target harvest and stock levels set by the manager can be very difficult. Together the results from Chapter 3 and 4 suggests that selling a single licenses would greatly simplify the management of the fishery and yield higher income levels. In Chapter 5, I compare the returns from selling a single global license relative to individual local licenses by developing a revenue sharing mechanism that can incorporate both approaches. The results show that a single license yields not only yields greater revenue levels, but also a more stable revenue stream over time.

The policy discussions in each of Chapter 4, 5, and 6 considers both PNA specific as well as broader fishery management perspectives. Chapter 6 is dedicated to policy implications specific to the PNA and the VDS considering insights from all three of the core chapters together. There are three general implications suggested by the results. First, a clear recommendation for a switch to harvest based licenses from the VDS may not be relevant. Second, the results strongly suggest the consideration of a single license that gives fishing vessels access to all countries. The final implication is that more research needs to conducted to validate these results, and examine the conditions necessary to support these results.

To provide some intuition about the problem, it may be useful to understand the general process in which fishing harvest and effort targets are set. First the manager determines the steady state stock levels that correspond to a management goal. Harvest rates that will maintain this steady state stock level are then determined, and an effort level that will achieve this harvest level is also found. Under output regulation, licenses are sold based on the harvest level. Under input regulation, licenses are sold based on the effort level. Under ideal circumstances the manager has perfect information about the world and would set an effort level that achieves the exact harvest target. In this case the two management schemes would be identical. However, the manager does not have perfect information about the world, and it is therefore very difficult to set an effort level which would achieve the exact target harvest levels. One example why this can be so hard is fishermen behavior called effort creep, where limiting effort levels by the manager leads to investments into fishing technology to increase productivity and catch more fish. Usually these investments are made without the knowledge of the fishery manager to achieve higher profit levels. A key simplifying assumption made by the standard model is that the fishing vessels are identical. This makes characterizing the solution simpler, but does not address the perfect information assumption even though the results under input and output regulation are identical.

The majority of studies examining fisheries management generally assume that fishermen are included as primary stakeholders, such that their welfare is a key consideration. The approach taken in each of the chapters presented in this thesis is that the welfare of the fishing vessels are secondary to the PNA member countries. The main reason for this is that the majority of the fishing fleet are foreign fishing vessels who have very little influence on the policies of the PNA and are generally not concerned about the welfare of the member countries. These foreign fishing fleets have long enjoyed highly lucrative returns at the expense of PNA members, and this viewpoint serves to shift focus towards the PNA's efforts to improve their returns from this fishery.

Chapter 2

The Parties to the Nauru Agreement and the Vessel Day Scheme

The majority of countries in the Central and West Pacific are at low levels of development. Aside from significant marine resources, most have very few natural resources. Revenues from fisheries within their EEZ provide an important source of income for these countries. The Pacific Islands Forum Fisheries Agency (FFA) was established in 1979 to facilitate regional co-operation and co-ordination between Pacific Island countries (PIC) with respect to fisheries policies. After the adoption of the exclusive economic zones (EEZ) in 1982, the majority of fishing in PIC waters were carried out by distant water fishing nations, as the island nations had no capacity for commercial fishing. However distant water fishing nations strategized in bilateral negotiations to reduce access fees to fisheries resources, and commercial fishing fleets under-reported their catch sizes to further reduce fees.

As a result, in 1982 the seven countries in the FFA with the most productive tuna fisheries formed the Parties to the Nauru Agreement in an effort to coordinate their approach to foreign fishing fleets. The primary goal was to improve access fee payments, improve catch and effort data, as well as maintain a sustainable harvest of the resource. The formation of the PNA allowed the members to impose rules governing the conduct of any vessel that wanted to fish for tuna in their EEZ. Despite these efforts, the economic rents from the commercial harvesting of tuna did not increase as expected, as fishing vessels still under-reported their catch sizes. It was difficult for officials to correctly evaluate the catch size as the quota system depended on log book and observer data, and it was not mandatory for vessels to unload their catch at predetermined ports for verification (Havice 2013).

	2010	**2011**	**2012**	**2013**	**2014**	**2015**
PNA EEZ	44,253	47,403	42,855	43,808	43,060	32,798
PNA AW	6,273	8,670	8,811	7,636	6,775	3,942
Total	50,526	56,073	51,666	51,444	49,836	36,739

Table 2.1: Purse seine log-sheet effort days of fishing vessels operating in PNA EEZ and archipelagic waters. Source: WCPF (2014)

In 2007, the PNA introduced an effort based management scheme known as the Vessel Day Scheme (VDS). A limit on total allowable effort (TAE) fishing days in a season is

Vessel Length	Frequency
0-50	8
51-60	22
61-70	76
71-80	145
81-90	9
91-100	2
100+	6
Total	268

Table 2.2: Purse seine fishing vessels in good standing and approved to operate in FFA EEZ and archipelagic waters,as of August 2016. Source: FFA (2016a)

	2008	2009	2010	2011	2012	2013	2014	2015
FSM	136,513	125,179	152,702	152,396	181,377	209,345	133,406	161,009
Kiribati	227,940	304,217	185,147	187,186	534,558	283,861	707,278	616,874
RMI	25,268	12,956	17,369	20,853	24,836	39,655	77,248	30,352
Nauru	62,755	61,280	108,580	97,743	52,138	163,404	179,269	66,527
Palau	4,040	950	347	0	737	310	2,670	185
PNG	493,040	480,520	726,652	619,763	580,593	585,877	336,709	186,247
Solomon Is.	123,434	117,235	162,989	158,197	77,363	111,456	57,015	102,794
Tuvalu	40,010	62,858	64,791	55,983	66,437	54,155	95,919	78,999
Total	1,113,000	1,165,195	1,418,577	1,292,121	1,518,039	1,448,063	1,589,514	1,242,987

Table 2.3: Catch size in thousands of metric tonnes per PNA country. Source: FFA (2016a)

	2008	2009	2010	2011	2012	2013	2014	2015
FSM	245	159	209	290	395	422	212	226
Kiribati	404	359	241	333	1172	597	1067	773
RMI	44	16	23	37	54	83	116	40
Nauru	110	74	144	172	114	344	271	86
Palau	8	1.5	0.53	0	1.8	0.54	6.4	0.25
PNG	878	604	1,018	1,159	1,282	1,227	548	260
Solomon Is.	217	147	214	283	170	235	91	134
Tuvalu	69	74	83	98	143	113	142	96
Total	1,975	1,435	1,933	2,372	3,332	3,022	2,453	1,615

Table 2.4: Estimated value of catch in millions of USD per PNA country. Source: FFA (2016a)

distributed to members based on historical catch data and the proportion of total stock in each country. Licenses bought from one country are valid only in the EEZ of that country. License days for parties could be sold between PNA members to allow for variability in income due to differences in fish stocks and other shocks. The revenues from the VDS depends on two taxes. The first is an access fee to register vessels with the PNA, which

	2008	2009	2010	2011	2012	2013	2014	2015
FSM	17	20	18	19	27	35	47	50
Kiribati	27	22	39	31	60	84	127	146
RMI	3.6	2.2	2.9	7.2	7.3	11	17	20
Nauru	10	6.7	12	13	11	13	21	35
Palau	2.3	0.97	1.6	1.8	4.7	5.4	5.8	8.4
PNG	46	31	55	62	71	77	93	94
Solomon Is.	18	15	19	24	23	25	27	41
Tuvalu	7.9	7.5	9	9.1	9.6	12	14	27
Total	131.8	105.37	156.5	167.1	213.6	262.4	351.8	421.4

Table 2.5: Total revenue from fisheries in millions of USD per PNA country. Includes all sources - US treaty, longlines access fees, as well as purse seine and other bilateral fishing fees. Source: FFA (2016a)

	2010	2011	2012	2013	2014	2015	2016
Pacific Island	62	64	75	83	94	98	102
Foreign	211	202	204	189	191	181	137
Total	273	266	279	272	285	279	239

Table 2.6: Number of fishing vessels operating in PNA EEZ. Source: WCPF (2014)

allows vessels to bid for licenses. The second is the price of a license (for individual vessel days) which allows vessels to fish. Licenses are auctioned by each country over the course of a season with full discretion over the format and timing of the auction. Licenses are specific to each country and allow vessels to fish only in the waters of the country that they bought the licenses from. Licenses have a mandatory reserve price which applies to the licenses for all the countries set by the PNA to discourage fishing vessels from strategizing to reduce prices. When the VDS was introduced in 2007, licenses were sold at a minimum of US $5,000 per day. The minimum price of a vessel day has increased to the current level of US $8,000 (PNA 2014).

The VDS discriminates fishing vessels based on length, which is expected to account for the assumption that larger vessels are more productive and can catch more fish in a given time. Table 2.2 shows that purse-seine fishing vessels operating in the PNA are not equivalent in size. Tidd et al. (2016) examined the PNA purse seine fleet of approximately 105 to 135 vessels over an 18 year period from 1993 to 2010, to determine the growth in productivity of the fishing fleet. They found that from the sample of 56 purse seiners who operated within the fishery over all 18 years, 27 showed significant increases in productivity levels, 26 showed no significant increases in productivity, and 2 showed negative productivity growth. Growth in productivity for the 27 vessels varied from 11 percent to 215 percent, demonstrating significant heterogeneity in productivity levels of vessels operating in the PNA fishery. The study concluded that the majority of the change in productivity was attributed to adoption of new technology rather than changes in effort levels. This is a prime example of 'effort creep', a term which describes the tendency of fishing vessels to improve their productivity levels to offset regulation designed to reduce harvest levels. Another study by Hoff (2006) of 49 vessels in the danish purse-seine fleet operating in the north sea, over 11 years from 1988 to 1999, found even higher variations in productivity growth levels, from 23 percent to 490 percent.

Vessels under 50 meters are assigned half a day, 50 to 80 meters are assigned one day, and 80 meters or more are assigned 1.5 days. Fishing time begins as soon as a vessel enters a EEZ, with strictly enforced exceptions. The key advantage of the VDS is the simplification of the monitoring process which has been crucial to its success. All fishing vessels are required to have GPS tracking systems, and observers from the PNA on board. The significant disadvantage of the VDS is that there are no limits on how much fish can be caught. Since the implementation of the VDS, the TAC set by members has decreased slightly from 35,738 days in 2008 to 45,136 in 2012. However, the number of days actually used by the members has increased from 31,432 in 2008 to 41,591 in 2012 (Havice 2013).

Economic analysis specific to the case of the PNA and the VDS is limited. Clarke and G. R. Munro (1987), Clarke and G. R. Munro (1991) modeled the PNA and DWFN interactions through a principal-agent game. These games look at mechanisms that the principal (PNA) can impose to induce agents (fishing vessels) to behave in a certain manner. In this case the mechanisms examined at were two taxes on catch and on effort respectively. They concluded that use of either taxes individually would not result in an optimal profit maximizing outcome for the PNA because of distortions to the incentives of fishing vessels. Instead, if a tax-subsidy scheme were used with the both types of taxes, a first best optimal solution would result. However, implementation of such a scheme would most likely not be feasible. Tokunaga (2015) looked at the related problem of transboundary fish stocks with non-seasonal movements. She concluded that prices should be set according to the level of stock a country has. The implication is that the PNA should set their prices independently of each other rather than a single overall price. A report by Deiye 2007 considered side payments as a component of a long-term access agreement for DWFN to the fishing grounds of Nauru. The paper arose out of concerns about revenue fluctuations from the adaptation of the VDS. The findings suggest that the side payments to the VDS as the best option to ensure long term revenue stability with the highest returns (Deiye 2007).

An independent review of the VDS was conducted by Anarson (2014) at the request of the PNA. The review was comprehensive and made several recommendations related to governance, design of catch share and license allocation mechanisms, compliance and transparency, optimal license levels and prices, as well as legal aspects of the VDS. Two recommendations were made for further examination of two issues. The first is a switch to harvest based licensing from the current effort based licensing. This issue has also been discussed at meetings by the PNA (PNA 2012). The second is examination of a homogeneous license that can be used over multiple countries. These two issues are important as they would also include consideration of several other recommendations made in the report. For example, optimal levels of licenses as well as prices would be key components of any study that would look at these two issues. A broad review of the global state of foreign fishing agreements was conducted by the World Bank (Arthur et al. 2014) which made similar recommendations to the VDS review.

A key issue that is affecting fisheries worldwide is the prevalence of illegal and unreported fishing (IUU). The World Bank report by Anarson, Kobayashi, and Fontaubert (2017) estimates the worldwide loss from IUU at $83 billion in 2012. This is also a serious issue for the Pacific tuna fishery as a whole, with an estimate by the Forum Fisheries Agency (FFA 2016b) of $600 million worth of product either harvested or transhipped involving IUU activity. The Pacific countries are actively working to improve monitoring and surveillance, however the FFA (2016b) report also suggests that the majority of IUU is by fishing vessels that are licensed to operate in the Pacific region. This has important implications for the PNA and the VDS as this suggests that stronger measures are required to improve monitoring of fishing vessels. This is a key consideration on whether a switch to harvest based licenses will be successful.

Chapter 3

Heterogeneous Fishing Vessel Model: Single Country Analysis

3.1 Introduction

As a resource manager, the PNA faces two challenges. The first is deciding as a collective the total number of licenses to be sold to the fishing vessels. This determines the total effort expended in the fishery, and in theory also determines the amount of tuna caught. If the TAC is too high, there could be overfishing of the stock. If the TAC is too low, the PNA will not be maximizing the income from the fishery. The second challenge is to ensure that maximum revenues are derived from the sale of the licenses. Presently, the total allowable catch (TAC) is set together as a coalition and then shared among the member countries. The TAC determines the number of licenses, which are auctioned individually by each country to the fishing vessels. Each license is tied to the country that sold it, and so fishing vessels can only fish in the EEZ of the country that it bought the license from. There are no restrictions on the arrangements of the auctions, aside from a reserve price set by collective decision.

The primary goal of this study is to compare input regulation management scheme to an output regulation management scheme for a single country. The standard bio-economic model by Gordon (1954) and Smith (1968) predicts that harvest, stock levels and revenue under both management schemes are identical. An alternative methodology for evaluating and comparing each management scheme is required. I extend this standard model by introducing heterogeneity of fishing vessels into the analysis, which allows for differences between the solutions of the two management schemes to be determined. To the authors knowledge, this specific problem has yet to be examined in detail. While the assumption of heterogeneous fishermen is not new, the PNA problem is unique both in its size and scale, as well the combination of the different dynamics involved. The standard model is outlined as a benchmark, which allows for comparison of the heterogeneous model to the standard model.

In the standard bio-economic model, a stock of fish X grows over time according to a function $g(X)$, and decreases by a harvest function $h(X, E)$. This harvest function h depends on stock size X, fishing effort E, and fishing vessel productivity q. This productivity level q is also known as the catchability value, and represents the proportion of the stock that can be captured with one unit of effort E. Fishing effort over time within a body of water containing stock X, is a function of the net profits that can be derived from fishing activities. If stock levels are high, then holding other factors constant profit levels are also high which incentivize fishermen to enter the fishery.

In order to determine the harvest level and the corresponding effort E to apply to a fishery, the manager derives the stock size that corresponds to a particular management goal such as open access, maximum sustainable yield (MSY), or optimal extraction. In open access, steady state levels are found where net revenues are driven down to zero. In MSY, equilibrium is where the growth function of X is maximized. In optimal extraction, X and E are treated as control variables in a maximization problem and are determined simultaneously to find steady state levels.

The amount of fishing can be controlled by limiting the effort level expended by the fishing vessels, or by limiting the amount of fish caught. Under output regulation, licenses are sold based on the harvest level which effectively controls the amount of fish caught. Under input regulation, licenses are sold based on the effort level which controls the amount of effort expended. Under ideal circumstances the effort level that the manager sets will result in the exact target harvest level. However, in practice this is very difficult to achieve. One reason is that under input regulation fishing vessels have incentive to increase their productivity level to increase harvest rates while paying the same amount for licenses. In general, it is a problem related to the imperfect information that the fishery manager has about the fishery and the fishing vessels.

Despite this significant shortcoming, fishing vessel catchability value q is always assumed to be constant in the standard models. As a result, the standard model predicts that effort based and quota based management schemes are identical. In the real world fishing vessels in the same fishery can be heterogenous with respect to the amount that they catch. This characteristic can be explained by captains and crew with good experience and skill, who can consistently guide the fishing vessels to productive fishing grounds. Table 2.2 outlines the PNA fishing fleet as of 2016, which shows that fishing vessels within the PNA vary in size. Tidd et al. (2016) examined the PNA purse seine fleet from 1993 to 2010 and found significant heterogeneity in productivity growth levels of fishing vessels. This implies that the output regulation and input regulation will not achieve the same steady state stock levels in practice. The harvest rate could be underestimated if q represents a lower than average catchability rate of fishing vessels. Similarly, the harvest rate could be overestimated if the q represents a higher than average catchability rate of fishing vessels. If the fleet is large such as in the PNA, this could result in harvest rates significantly different from predicted targets.

Adopting the heterogeneous fishing vessels assumption offers several advantages that can overcome these issues. The primary advantage is that input and output regulation can have different steady state predictions for harvest, stock and revenue levels allowing for meaningful comparisons. Another advantage is that the marginal price that a fishing vessel is willing to pay for a fishing license can be identified, allowing for endogenous determination of participation in the fishery within the model. This reflects the real world where more productive fishing vessels are willing to pay different higher prices for the same license as a result of differing productivity and costs. A third advantage of heterogeneous catchability values is that it is possible to explore the effects of different auction mechanisms. Finally, the inclusion of heterogeneous fishing vessels into the standard models allows for examination of a multi-country fishery.

In the hetereogenous fishing vessels model, fishing vessels have a productivity value measured by the catchability coefficient q, which is drawn from some distribution $f(q)$. Fishing vessels behave as static optimizers, maximizing a linear profit function over the season. Define the marginal fisher as the fishing vessel which makes zero economic profit and has catchability rate $\bar{q}$. Fishing vessels with productivity levels below $\bar{q}$ will make negative economic profit and are not be able to participate in the fishery, and vessel above $\bar{q}$ will make positive economic profit. This implies that the equilibrium clearing price is determined by the cutoff catchability value $\bar{q}$, such that only fishing vessels who are productive enough can afford to buy licenses from the fishery. This allows the model to endogenously determine participation in the fishery.

I examine the single country case where a fishery manager dynamically determines the optimal output for maximizing revenues over the lifetime of the fishery. I characterize steady state conditions for open access, maximum sustainable yield, and optimal extraction. I provide a simulation based loosely on the parameters of the PNA and the Ecuadorian purse-seine fishing fleet, which is intended to demonstrate how the model operates. I include the standard textbook model as a benchmark for comparison.

The main result of this chapter is that the heterogeneous model shows that output regulation yields higher revenues to the fishery manager compared to input based regulation schemes. As a result revenue to fishing vessels is higher under input regulation relative to output regulation. The simulation exercise results reflects the theoretical predictions of the model. These findings suggests that the heterogeneous model provides more accurate estimations of harvest size because fishing vessel variability is inherent in the model. This offers not only a closer approximation of the real world, but also results in less sensitivity to an error in the estimation in the values of q. This is especially important for fisheries with large fishing fleets such as the PNA. These results leads to the policy recommendation that in a single country setting, output regulation should be adopted over output regulation if harvest levels can be monitored accurately. These results provide a foundation for an extension of the model to multiple countries, which is a closer match of the PNA case.

Only a handful of studies have examined the PNA problem specifically. Clarke and G. R. Munro (1987), Clarke and G. R. Munro (1991) modeled the PNA and DWFN interactions through a principal-agent game. They examined two taxes on catch and on effort that the principal (PNA) can impose to induce fishing vessels to behave in a certain manner. They concluded that use of either taxes individually would not result in an optimal profit maximizing outcome for the PNA because of distortions to the incentives of fishing vessels. Instead, a tax-subsidy scheme used with both types of taxes would result in a first best optimal solution. However, such a scheme would be complex and impractical to implement.

The majority of the literature on heterogeneous fishing vessels examines welfare effects to fishermen moving from open access or common pool resource management, to some type of property rights arrangement. Examining the case of the Texas shrimp fishery Johnson and Libecap (1982) were one of the first to identify heterogeneity in fishermen ability based on observed catch size. One approach to modeling heterogeneous fishermen focus on variations in cost between fishermen. Coglan and Pascoe (1999) show that using average performance measures is misleading in heterogeneous fisheries where costs vary among fishermen, and can lead to undesirable management outcomes. Grainger and Costello (2015) examine the transition from common pool to property rights, and find that there will be some opposition from some incumbent fishermen. Péreau et al. (2012) examine ITQ dynamics in a fishery with an explicit social objective and finds that success of an ITQ scheme is only achieved under very specific outcomes and depends on the degree of heterogeneity of the fishing vessels. Other approaches, similar to that taken in this study, focus on the variations in ability measured by productivity levels. Terrebonne

(1995) examines the welfare of heterogenenous fishermen, and finds that private ownership in the form of ITQs leads to an optimal outcome. Heaps (2003) re-examined the same problem and found that Terrebonne's results do not always hold, and that in transition from open access to ITQ fishermen welfare may actually decrease. Merrifield (1999) takes a different approach and suggests policies aimed at reducing heterogeneity in a bid to reach an efficient outcome.

This study assumes that the market for licenses is large, and that there is a single equilibrium price level where the market clears. Another key assumption is that fishing vessels profit functions are linear in cost. Once again this allows for a simpler model, which offsets the potential benefits of including a non-linear cost function. Overall it does not affect the conclusion of the study by a great deal, because the fishing vessels would have been identical with respect to costs associated with fishing. The model assumes no cost for countries to sell licenses. In the simulation exercise, I assume that fishing vessels productivity levels are uniformly distributed. The primary reason is for tractability in calculating the theoretical solutions. Other distribution functions such as the normal distribution could be better representation of the fishing fleet, however closed form theoretical solutions are difficult to characterize.

The paper is organized as follows. Section 3.2 outlines the model for the paper. Section 3.3 provides a numerical illustration of the model. Section 3.4 provides a discussion of the results and policy implications, and Section 3.5 concludes.

3.2 Model

Assume there is a country with a stock of tuna which grow according to a logistic function. This country sells fishing licenses which allows fishing vessels to operate in its waters. There is a fishing fleet of size N which can buy fishing licenses. In the standard model, fishing vessels are homogeneous. In the hetereogenous fishing vessels model, fishing vessels have a productivity value measured by the catchability coefficient q which is distributed according to some function $f(.)$. As a result the licenses have different values unique to each fishing vessel, which depend on how much fish each vessel can catch. The abundance of fish in a particular country is measured by the stock size X, which I assume is common information. As fishing vessels catch fish, they deplete the fish stock. I assume that the licenses are all sold at the beginning of the season, which implies a competitive market with significant demand from a high number of fishing vessels. More productive fishing vessels will catch more fish, and so they potentially have a higher valuation of a given license day, relative to a less productive fishing vessel.

As a baseline, I outline the standard Gordon-Smith model calculating optimal extraction, open access and maximum sustainable yield levels for each fishery. I then introduce into the Gordon-Smith model heterogeneous fishing vessels, and determine the clearing price of a fishing license under input and output control, as a function of the productivity level q of fishing vessels.

3.2.1 Homogenous Fishing Vessels

For the single country case, there are no possible inflows and outflows of tuna stocks from outside sources. Stock levels evolve according to the standard equation

$$\dot{X}_t = g(X_t) - h(X_t, E_t) \tag{3.1}$$

subject to

$$X_0 = \bar{X} \qquad > 0$$

$$E_t \geq 0$$

where $g(X_t)$ is a logistic growth function for the stock of fish X, and $h(X_t, E_t)$ is a harvest function which depends on the stock level and effort level E applied to the fishery. Effort $E = eN$ is the total fishing effort for all fishing vessels, where e is the effort level for each individual fishing vessel measured in days and N is the total number of fishing vessels. Given that there are a finite number of days in a year, for each time period there is a maximum effort level $E_{max} = e_{max}N$ that is equal to the maximum effort level in a season multiplied by the number of all the fishing vessels operating in the fishery.

For the homogeneous case I assume the standard textbook logistic growth function 3.2, and the Schaefer (1957) catch-effort relation for the harvest function 3.3.

$$g(X_t) = rX_t(1 - X_t/K) \tag{3.2}$$

$$h(X_t, E_t) = qX_tE_t \tag{3.3}$$

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Under open access there is no regulation on the amount of fishing in the fishery. The equation of motion for effort is equal to zero at equilibrium

$$\dot{E}_t = ph(X_t, E_t) - cE_t = 0 \tag{3.4}$$

Under the assumption that $K > \frac{c}{pq}$, the open access equilibrium stock level is

$$X_{OA} = \frac{c}{pq} \tag{3.5}$$

Substituting equation 3.5 into the equation of motion for stocks (equation 3.1) yields the open access equilibrium effort level.

$$E_{OA} = \frac{r}{q}(1 - \frac{c}{Kpq}) \tag{3.6}$$

Maximum Sustainable Yield

The logistical growth function $g(X)$ is maximized where $g'(X) = 0$. This yields the MSY equilibrium stock level.

$$X_{MSY} = \frac{K}{2} \tag{3.7}$$

Substituting this into the equation of motion for stocks (equation 3.1) yields the MSY equilibrium effort level.

$$E_{MSY} = \frac{r}{2q} \tag{3.8}$$

Optimal Extraction

The standard maximization problem for a fishery manager to optimize profit over the lifetime of the fishery is

$$\max_{E} \int_{0}^{\infty} e^{-\rho t}[(ph(X_t, E_t) - cE)]dt$$

subject to

$$\dot{X}_t = g(X_t) - h(X_t, E_t)$$

$$X_0 = \bar{X}, \quad E_0 = \bar{E}, \quad X_t \geq 0, \quad E_t \geq 0$$

The solution for X^* takes the following form, which can be positive or negative, however the positive root is the solution to the problem in this case and we disregard the negative root.[1]

$$X^* = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A} \tag{3.9}$$

where

$$A = \frac{2pr}{K}; B = pr - p\rho - \frac{cr}{qK}; C = \frac{\rho c}{q}$$

Substituting equation 3.9 into the equation of motion for stocks (equation 3.1) yields the optimal equilibrium (steady state) effort level E^*.

$$E^* = \frac{r}{q}(1 - \frac{X^*}{K}) \tag{3.10}$$

The optimal harvest strategy is a piecewise function which depends on the stock level in the fishery. This strategy results in a 'bang-bang' type of transition to steady state, and is a result of the infinitely elastic tuna price (constant price) assumption. If the stock level is above the steady state, the optimal harvest strategy is to apply maximum effort. At steady state stock levels, the optimal harvest strategy is to apply the effort rate that results in a harvest rate equal to the growth rate of the stock. At stock levels below steady state the optimal harvest rate is zero.

$$E(t) = \begin{cases} E_{max} & if \quad X(t) > X^* \\ E_* & if \quad X(t) = X^* \\ 0 & if \quad X(t) < X^* \end{cases} \tag{3.11}$$

Once the fishery manager finds the optimal stock level, the optimal harvest strategy and the corresponding optimal quota for the season can be found. In the case of input control or effort based regulation, the optimal amount of effort days becomes the total allowable effort (TAE) which are to be sold to fishing vessels. In the case of output control or a quota based regulation, the optimal harvest size becomes the total allowable catch (TAC) size to be sold to the vessels.

With the homogeneous vessels assumption, the relationship between the effort level and harvest level is constant. That is, it does not matter which regulation scheme is used as the resulting harvest level, effort levels and steady state stock levels are the same.

[1] See Appendix A for Derivation

3.2.2 Heterogenous Vessels

A critical assumption in the classic fishery managers problem outlined in Section 3.2.1 is that fishing vessels are heterogeneous. However, in reality some vessels may catch more than others, even if fishing vessels are physically identical in every way. This is known as the ‘good captain’ effect. This means that there is an element of heterogeneity in the catchability coefficient of fishing vessels. It follows that the optimal effort levels calculated assuming homogeneous fishing vessels may not achieve the target harvest or stock levels as it does not take into consideration the potential variation in harvest rates.

Assume that there is a continuum of N fishing vessels from $q_{min} = a$ to $q_{max} = b$. All fishing vessels are identical aside from the catchability value q. This catchability value q is distributed according to some probability density function $f(.)$. Let e represent the effort level of a single fishing vessel measured in days, which can vary from 0 to e_{max}, where e_{max} is the total possible number of days in a fishing season. I maintain the constant market price of tuna assumption, and so each vessel has incentive to fish the maximum number of days in a fishing season due to the linear profit function.

The approach used to determine the number of licenses to be sold for either input or output regulation is similar to the standard model. First, the fishery manager has to find the stock level that corresponds to the management goal. This stock level is then used to find the harvest and effort levels for each regulation scheme, which is then used to determine the number of licenses to sell. Under input regulation the licenses are sold as effort days, and under output regulation licenses are sold by tonnes of tuna caught.

If all fishing vessels are allowed to participate in the fishery, total harvest for time t can be found by summing the harvest level for all fishing vessels from productivity level a to b. Maintaining the Schaefer (1957) catch-effort relation for the harvest function from the standard model in 3.3, total harvest at time t is

$$h_t = \int_a^b qX_t eNf(q)dq \tag{3.12}$$

If the fishery is regulated according to some management goal such as MSY or optimal extraction, assuming a sufficiently large fishing fleet, not all fishing vessels will be able to participate. Suppose that licenses are sold or distributed to fishing vessels according to some competitive allocation method based on the fishing vessels marginal value for the licenses. Let $\bar{q}$ be the cutoff productivity level of the fishing vessel whose marginal value for a fishing license is equal to zero. This implies that all fishing vessels with $q \geq \bar{q}$ should participate since they have zero or positive marginal value for a license, but fishing vessels with $q < \bar{q}$ are better off not participating in the fishery since their marginal value for a license will be negative. This further implies that $\bar{q}$ is where the equilibrium price $\bar{w}$ of the licenses is determined. It also follows that only vessels with a catchability coefficient $\bar{q}$ and higher are able to pay the equilibrium price $\bar{w}$, and are the only vessels able to acquire licenses to fish. The tighter the regulation scheme, the less licenses there will be to sell, and the closer $\bar{q}$ will be to b which implies less vessels participating. Conversely, the more relaxed the regulation scheme is, the more licenses there are to sell, and the closer $\bar{q}$ will be to a which implies more vessels participating.

Total harvest under regulation is the sum of harvest for all fishing vessels from q_{max} to $\bar{q}$. Since $\bar{q}$ can vary over time with the stock level, it is denoted with a t subscript as $\bar{q}_t$.

$$h_t = \int_{\bar{q}_t}^{b} qX_teNf(q)dq \tag{3.13}$$

Define the total number of vessels who can bid for licenses as the potential effort level

$$E = eN$$

If all fishing vessels are allowed to participate in the fishery, actual fishing effort level expended in the fishery is equal to the potential effort level, $\bar{E} = E$. Under regulation, fishing vessels with $\bar{q}_t \leq q \leq q_{max}$ are the only vessels able to buy licenses to fish and participate. This means actual effort expended in time t is E multiplied by the probability of $\bar{q}_t \leq q \leq q_{max}$.

$$\bar{E}(\bar{q}_t) = eNPr[\bar{q}_t \leq q \leq q_{max}] \tag{3.14}$$

The equation of motion for stocks in the heterogeneous model is

$$\dot{X}_t = g(X) - h(X, \bar{q}_t) \tag{3.15}$$

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Finding open access equilibrium in the heterogeneous model requires two equations to solve for open access stock levels X^{OA}, and open access cutoff catchability value $\bar{q}^{OA}$. The first equation is the profit function of the marginal fishing vessel under open access conditions, which is set to zero.

$$ph(X, \bar{q}^{OA}) - ce = 0 \tag{3.16}$$

The intuition behind this equation is that in open access all fishing vessels are free to fish without paying any licenses, and fishing vessels will only participate if it is profitable. The second equation is the equation of motion for stocks 3.15, which is also set to zero.

$$\dot{X}_t = g(X) - h(X, \bar{q}) = 0$$

This equation implies that given the open access effort level derived from $\bar{q}^{OA}$, the fishery will reach a stable level. Equation 3.16 along with 3.15 form two simultaneous equations that determine the solution for $\bar{q}^{OA}$ and X^{OA}. Once $\bar{q}^{OA}$ is known, the open access effort level $\bar{E}^{OA}$ can be found by substituting $\bar{q}^{OA}$ into 3.14.

The definition of open access is that there is no restriction on fishing activities, and fishing vessels are free to exploit the fishery as much as they wish. In general, fishing vessels are only limited by the market conditions and the length of the fishing season. As long as fishing vessels are profitable they will continue to fish. One of the consequences of the linear profit function that I have assumed for fishing vessels is that profits increase linearly with stock levels. The only limit on their activity is the amount of effort that they can expend in a season, which is fixed at e_{max}. Holding the cost of fishing c, the market price of fish p constant, at a certain stock level each fishing vessel has a stock level below which they will not be profitable. This implies that at some X^{OA} and some $\bar{q}^{OA}$, the fishery will reach open access equilibrium where no vessel will have incentive to enter the fishery due to very low profit levels.

Optimal Extraction

The maximization problem for a fishery manager with heterogeneous catchability coefficients becomes

$$\max_{\bar{q}} \int_0^\infty e^{-\rho t}[(ph(X_t, \bar{q}_t) - cE(\bar{q}_t)]dt$$

subject to

$$\dot{X}_t = g(X_t) - h(X_t, \bar{q}_t)$$

$$X(t) \geq 0, \quad E(t) \geq 0$$

To solve this problem, the Hamiltonian equation is

$$H = ph(X_t, \bar{q}_t) - cE(\bar{q}_t) + \lambda_t[g(X_t) - h(X_t, \bar{q}_t)]$$

Applying the maximum principle, the following conditions are derived

$$\frac{\partial H}{\partial \bar{q}_t} = ph_{\bar{q}}(X_t, \bar{q}_t) - cE_{\bar{q}}(\bar{q}_t) - \lambda h_{\bar{q}}(X_t, \bar{q}_t) = 0 \tag{3.17}$$

$$\dot{\lambda}_t = \lambda\rho - ph_x(X_t, \bar{q}_t) - \lambda[g_x(X_t) - h_x(X_t, \bar{q}_t)] \tag{3.18}$$

$$\dot{X}_t = g(X_t) - h(X_t, \bar{q}_t) \tag{3.19}$$

Applying the steady state condition $\dot{X} = 0$, the following equilibrium condition is found. (For derivations refer to Appendix A)

$$\Big(p - \frac{cE_{\bar{q}}}{h_{\bar{q}}}\Big)\rho = \Big(p - \frac{cE_{\bar{q}}}{h_{\bar{q}}}\Big)g_x + \frac{cE_{\bar{q}}}{X_t h_{\bar{q}}}g(X_t) \tag{3.20}$$

Rearranging 3.20 gives a quadratic expression for $\bar{X}^*$, where the positive root is the solution. Substituting $\bar{X}^*$ into the equation of motion for stocks yields the optimal equilibrium (steady state) cutoff catchability level $\bar{q}$. Together $\bar{X}^*$ and equation $\bar{q}$ form a system of equations with two unknowns, where the solution to the system is the solution to the model. Substituting $\bar{q}^*$ into equation 3.14 yields the optimal steady state effort level $\bar{E}^*$.

To check for the stability of the system of equations $\dot{X} = f(X, \bar{q})$ and $\dot{E} = g(X, \bar{q})$), I compute the eigenvalues which can determine stability. Appendix 3.B provides the derivations for these equations. The system can then be evaluated with parameters under the simulation exercise.

Determining Equilibrium Price w

In order to determine the equilibrium price and $\bar{q}$, I examine the demand for licenses by the fishing vessels. A representative fishing vessel pays a fee to fish over one season only. By backward induction, it's dominant strategy is to extract as much fish as possible. In the standard model fishing vessels are identical. In the heterogenous model fishing vessels catchability coefficient q which determines the productivity of the fishing vessels, varies from vessel to vessel.

Output Control

Homogeneous Model
In the quota based regulation case, the profit maximizing problem for fisherman k

$$\max_e ph(X, e_k) - w_k h(X, e_k) - ce_k$$

subject to

$$h(X, e_k) = q_k X e_k$$

$$e_{min} \leq e \leq e_{max}$$

where w is the price of a fishing licenses sold per ton of harvest caught, p is the market price of a ton of tuna which fishermen sell to wholesalers, and c is the marginal cost of fishing effort. The lower limit e_{min} represents the limit at which a fisherman will not be able to make a profit, and the upper limits e_{max} represents the finite amount of fishing days in a season. The first order condition is

$$ph_e(X, e) - wh_e(X, e_k) - c = 0$$

Fishermen maximize profits where the marginal benefit (price per ton of tuna p) of a fishing day equals the marginal cost of a fishing day $(w_k - \frac{c}{qx})$. Rearranging, the price per unit of harvest that vessel k is willing to pay is

$$w_h^k = p - \frac{c}{q_k X} \tag{3.21}$$

Since all fishing vessels are the same in the standard model, $w_h^k = w_h$. This means that that $w_h = w_h^*$ is the clearing price at steady state X^*. In the standard model there is no way to determine which specific vessels get the licenses.

Heterogeneous Model
Although fishinging vessels differ by productivity level in the heterogeneous model, the maximization problem for each individual fishing vessel, and expression for the price per unit of harvest each vessel is willing to pay (3.21) is identical to the homogeneous case.

An implication of equation 3.21 is that fishermen with higher productivity levels q are able to pay a higher price for a license. Let $w_{\bar{h}}^*$ be the license clearing price where all the licenses are sold, and assume that there is enough demand such that for at least one fisherman, $w_{\bar{h}}^* \geq w_h^k$. An implication of the linear profit function chosen above is that all fishing vessels will demand the highest possible number of licenses. In the case of output control this is equal to the maximum possible catch per day of a fishing vessel measured by the size of the hold[2], multiplied by the number of days on a season. Fishermen who are able to pay $w_h^k \geq w_{\bar{h}}^*$ will demand the maximum number of licenses, and those who cannot will demand zero licenses. At the clearing price, there is a cutoff catchability value $\bar{q}$ such that

$$w_{\bar{h}}^* = p - \frac{c}{\bar{q}\bar{X}} \tag{3.22}$$

Any vessels with $q_k \geq \bar{q}$ will be able to buy licenses, and those with $q_k < \bar{q}$ will not. The optimal strategy for fishing vessel k is

[2]Assuming one fishing trip per day

$$e_k = \begin{cases} e_{max} & if \quad q_k \geq \bar{q} \\ 0 & if \quad q_k < \bar{q} \end{cases} \tag{3.23}$$

Rearranging 3.22 for $\bar{q}^*$ yields the inverse demand for licenses. Substituting this into the harvest equation gives the optimal harvest level which is supported at steady state.

$$h^* = \left(b^2 - \left[\frac{c}{\bar{X}^*(p - w_{\bar{h}}^*)}\right]^2\right)\frac{\bar{X}^* eN}{2(b-a)}$$

Substituting the steady state cutoff catchability value $\bar{q}^*$ from 3.46 into equation 3.22 above, we can determine the equilibrium license price for output control case as

$$w_{\bar{h}}^* = p - \frac{c}{\bar{X}^*\left[b^2 - \frac{2(b-a)}{eN}(r - \frac{r\bar{X}^*}{K})\right]^{\frac{1}{2}}} \tag{3.24}$$

Input Control

Homogeneous Model

In the effort based regulation case, the profit maximizing problem for fisherman k is

$$\max_{e} ph(X, e_k) - w_k e_k - ce$$

which is subject to the same conditions as in the output control case. The first order condition is

$$ph_e(X, e_k) - w_k - c = 0$$

Fishermen maximize profits where the marginal benefit (price per ton of tuna p) of a fishing day equals the marginal cost of a fishing day $(\frac{w_k - c}{qx})$. Rearranging, the price per unit of effort that vessel k is willing to pay is

$$w_E^k = pq_k X - c \tag{3.25}$$

In the standard model $w_E^k = w_E$ since all fishing vessels are the same. This means that that $w_E = w_E^*$ is the clearing price at steady state X^*. In the standard model there is no way to determine which specific vessels get the licenses.

Heterogeneous Model

Once again, although fishing vessels differ by productivity level in the heterogeneous model, the maximization problem for each individual fishing vessel, and expression for the price for a unit of effort each vessel is willing to pay (3.25) is identical to the homogeneous case.

An implication of equation 3.25 is that fishermen with higher productivity levels q, are able to pay a higher price for a license. Let $w_{\bar{E}}^*$ be the license clearing price where all the licenses are sold, and assume that there is enough demand such that for at least one fisherman, $w_{\bar{E}}^* \geq w_E^k$. An implication of the linear profit function chosen above, is that all fishing vessels will demand the highest possible number of licenses. In the case of input control, this is equal to the length of the season divided by the unit of effort. Fishermen who are able to pay $w_E^k \geq w_{\bar{E}}^*$ will demand the maximum number of days in the season, and those who cannot will demand zero days. There is a cutoff catchability value $\bar{q}$, such that

$$w^*_{\bar{E}} = p\bar{q}\bar{X} - c \tag{3.26}$$

Any vessels with $q_k \geq \bar{q}$ will be able to buy licenses, and those with $q_k < \bar{q}$ will not. The optimal strategy for fishing vessel k is

$$e_k = \begin{cases} e_{max} & if \quad q_k \geq \bar{q} \\ 0 & if \quad q_k < \bar{q} \end{cases} \tag{3.27}$$

Rearranging 3.26 for $\bar{q}^*$ yields the inverse demand for licenses. Substituting this into the effort equation gives the optimal effort level which is supported at steady state.

$$\bar{E}^* = eN\Big(1 - \frac{w^*_{\bar{E}} + c}{p\bar{X}^*(b-a)} - \frac{a}{b-a}\Big) \tag{3.28}$$

Substituting the steady state cutoff catchability value $\bar{q}^*$ from 3.46 into equation 3.26 above, we can determine the equilibrium license price for input control case as

$$w^*_E = p\bar{X}^*\big[b^2 - \frac{2(b-a)}{eN}(r - \frac{r\bar{X}^*}{K})\big]^{\frac{1}{2}} - c \tag{3.29}$$

3.2.3 Steady State Characteristics

This section compares the steady state characteristics of standard model with the modified heterogeneous model for the single country case and the multi-country case, with respect to revenue.

Revenue

Proposition 1. *For a single country which sells licenses allowing vessels to fish, under the assumption of competitive behavior and heterogeneous fishers, revenue received by the country under output regulation is always greater than under input regulation.*

Proof. Under output regulation, total revenue from each individual vessel is the price of a license multiplied by the harvest ($w_H q_i X e_i$). Under input regulation total revenue from each individual vessel to the country is the price of a license multiplied by effort ($w_E e_i$). The key is to note that q only appears in the revenue equation for output regulation $w_H q_i X e_i$, and that effort level e is the same for all fishing vessels.

For the heterogeneous fishermen, q follows some distribution. By definition of a distribution, there is a continuum of q values that are greater than $\bar{q}$ and less than b. Since the marginal fisher who makes zero profit is the same under both input and output regulation (fisherman with $q = \bar{q}$), it follows that revenue under output regulation must be higher than revenue under input regulation.

$$\int_{\bar{q}}^{b} w_H q X e dq > \int_{\bar{q}}^{b} w_E e dq$$

□

This result is independent of the distribution of q. This result also holds under the assumption of non-linear costs for fishing vessels with respect to stock size X.

Proposition 2. *Under the assumption of competitive behavior, all fishing vessels aside from the marginal vessel who participate in a fishery through license purchase have positive rent under both regulation schemes. However, rent under output regulation is always less than rent under input regulation.*

Proof. This result is direct result of Propositions 1. To show that all fishing vessels with $q > \bar{q}$ have positive revenue, consider fishing vessel j which has a $q_j > \bar{q}$ and fishing vessel i which has $q_i = \bar{q}$. For the marginal fisher i, it is true that rent is zero. So, under input regulation vessel j must have positive profit since

$$pq_jXe_j > pq_iXe_i$$

Similarly, under output regulation vessel j must have positive profit since

$$p - \frac{c}{q_jX} > p - \frac{c}{q_iX}$$

Finally, since it has been shown that $w_Hq_jXe_j > w_Ee_j$ it is straightforward result that revenue under output regulation is greater than revenue under input regulation for the manager. □

The intuition behind Proposition 1 and 2 is that under input control, the effort level demanded by each vessel who buy the license is the same, which is the maximum days in a season (e_{max}). In addition, with the assumption of perfect competition, the price that all fishing vessels pay for a license to fish for a day (or the entire season) is the same, which is the price of the marginal fishing vessel with $q = \bar{q}$. However, since productivity levels are not equivalent across fishing vessels, the harvest size over a day (or the entire season) for each boat will vary. More productive fishing vessels will catch more fish relative to less productive vessels. In effect, the price per ton of tuna harvested under input regulation will be less for high q vessels relative to fishing vessels with a lower q. This represents additional rent for fishing vessels which is gained from fishery owners revenue.

For output regulation, even though high q vessels may catch more fish in a given amount of time, all fishing vessels will pay the same price per ton of fish caught, which is the price of the marginal fishing vessel with $q = \bar{q}$. It follows that fishing vessels would accrue less profit relative to input regulation, which means higher revenues for the fishery owner.

The reason that the standard model does not have this prediction for revenues is that it assumes that all fishing vessels are the same. This means that there are no differences between the price per ton of fish caught under output regulation and input regulation. The difference in the level of revenue from the two management schemes depends on the spread of the productivity levels of the fishing vessels. Under input control if the range between q_{max} and q_{min} is high, then the marginal fishing vessel (with $q = \bar{q}$) may be catching much less than the higher q vessels. In this case the high q fishing vessels are underpaying potentially by a large amount, and gaining potentially much higher rent then they would have under output regulation.

3.3 Application

The purpose of this section is to illustrate how the homogenous and heterogenous models compare to each other using parameter estimates that roughly approximate the PNA fishery for skipjack tuna. First I outline a functional form of the model assuming a uniform distribution of q values. Then I determine approximate parameter estimates for the PNA case. Finally I provide a simulation based on the parameter values.

Model Under Uniform Distribution

Under the assumption that $f(q)$ is a uniform probability density function with $q_{max} = b$ and $q_{min} = a$, the harvest equation h from 3.13 becomes

$$h = \int_{\bar{q}_t}^{b} qX_t e\Big(\frac{N}{b-a}\Big) dq = \Big[\frac{q^2}{2(b-a)} X_t eN\Big]_{\bar{q}}^{b}$$

$$h(X, \bar{q}) = (b^2 - \bar{q}_t^2)\frac{X_t eN}{2(b-a)} \tag{3.30}$$

Total actual effort from 3.14 is

$$\bar{E}(\bar{q}) = eNPr[\bar{q}_t \leq q \leq q_{max}] = eN\Big(1 - \frac{\bar{q}_t - a}{b-a}\Big) = eN\Big(\frac{b - \bar{q}_t}{b-a}\Big) \tag{3.31}$$

The equation of motion for stocks becomes

$$\dot{X}_t = \Big(rX_t - \frac{rX_t^2}{K}\Big) - (b^2 - \bar{q}_t^2)\frac{X_t eN}{2(b-a)} \tag{3.32}$$

Open Access
Finding the open access stock level requires solving two equations with two unknowns, $\bar{q}^{OA}$ and X^{OA}. The first equation is the profit function from the marginal fisher, who has zero profit

$$p\bar{q}^{OA}Xe - ce = 0$$

The second equation is the equation of motion for stocks which is also set to zero.

$$\dot{X}_t = \Big(rX_t - \frac{rX_t^2}{K}\Big) - (b^2 - \bar{q}_t^2)\frac{X_t eN}{2(b-a)} = 0$$

Open access effort level is found by substituting $\bar{q}^{OA}$ into 3.31.

$$\bar{E}^{OA} = eN\Big(\frac{b - \bar{q}^{OA}}{b-a}\Big)$$

Optimal Extraction

From 3.20 I have the following equilibrium condition.

$$\Big(p - \frac{cE_{\bar{q}}}{h_{\bar{q}}}\Big)\rho = \Big(p - \frac{cE_{\bar{q}}}{h_{\bar{q}}}\Big)g_x + \frac{cE_{\bar{q}}}{X_t h_{\bar{q}}} g(X_t)$$

The functional form of the equilibrium condition is

$$\Big(p - \frac{c}{X_t\bar{q}_t}\Big)\rho = \Big(p - \frac{c}{X_t\bar{q}_t}\Big)(r - \frac{2rX}{K}) + \frac{c}{X_t^2\bar{q}_t}\Big(rx - \frac{rX^2}{K}\Big)$$

Rearranging gives

$$(\frac{2pr}{K})X^2 + (p\rho - pr - \frac{cr}{K\bar{q}_t})X - \frac{\rho c}{\bar{q}_t} = 0$$

An expression for $\bar{X}$ takes the following form, where the positive root is the solution.

$$\bar{X} = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A} \tag{3.33}$$

where

$$A = \frac{2pr}{K}; B = p\rho - pr - \frac{cr}{K\bar{q}_t}; C = \frac{\rho c}{\bar{q}_t}$$

Substituting $\bar{X}$ into the equation of motion for stocks yields the optimal equilibrium (steady state) cutoff catchability level $\bar{q}$.

$$\bar{q} = \big[b^2 - \frac{2(b-a)}{eN}(r - \frac{rX^*}{K})\big]^{\frac{1}{2}} \tag{3.34}$$

Together equation 3.52 and equation 3.46 form a system of equations with two unknowns. The solutions to the system is the solution to the model, $\bar{X}^*$ and $\bar{q}^*$. Substituting $\bar{q}^*$ into equation 3.31 yields the optimal steady state effort level $\bar{E}^*$.

$$\bar{E}^* = eN\Big(1 - \frac{\bar{q}^* - a}{b - a}\Big) \tag{3.35}$$

Appendix 3.B provides the derivations for these equations.

Parameter Estimates

According to Rice et al. (2014) the maximum sustainable yield (MSY) harvest for all tuna stocks including skipjack in the entire WCPO region is roughly about 1.5 million metric tons. Given that 1.5 million tons has been where the total PNA harvest of only skipjack tuna has been fluctuating around since 2010, I use this number as the baseline for this illustration. Assuming a logistic growth function, from equation 3.7, $X_{MSY} = K/2$. The carrying capacity equation is then equal to $K = \frac{\dot{X}4}{r}$, which yields a K value of 16.6 million tonnes for the entire WCPO region. Since the majority of the catch of skipjack in the WCPO region is from the PNA countries, for simplicity I let $K = 16$ million tons. For an estimate of the intrinsic growth rate of the stock r, a range of 0.1 to 0.34 was estimated by the Pacific Fishery Management Council (2016). For tractability I let the discount factor $\rho = 0.1$.

The number of fishing days per vessel is required to determine an estimate for q. From the number of fishing vessels in the PNA (Table 2.6) and the figures of fishing vessel effort days (Table 2.1) provided by the WCPF (2014), the average number of fishing days per vessel for each year from 2010 to 2015 is approximately 180 days, or about 6 months. This number is not definitive because the TAE is split among 7 countries, where some get more and others less. Regardless it can provide a baseline for this illustration.

Dividing the total number of fishing vessels for each year by the total catch yields a number for average total catch per vessel per year from 2010 to 2015 (Table 3.1, row 3). Taking the average, this is equal to a yearly catch of 5,220 tons per boat. This corresponds to a daily average catch of 29 tons. Dividing the yearly catch by the MSY stock size since the WCPO has been operating at this figure since , the average annual value of q is 0.0065 over the years 2010 to 2015. This figure corresponds to about 29 tons of tuna caught per day per boat assuming a six month fishing season. This figure is a little higher than that reported by the FFA (2016a), where their average over this period is around 25 tons per effort day. Given q, a range of $q_{min} < q < q_{max}$ is required for the heterogenous case. To simplify, I let $q = 0.006$ for the heterogenous case, then I vary a and $b =$ around this value to determine how revenue changes.

	2010	**2011**	**2012**	**2013**	**2014**	**2015**	**Average**
Effort day/vessel	185	211	185	189	175	132	179
CPUE	7410	6625	7666	7422	8234	6688	7341
Yearly Catch/vessel	5211	4929	5513	5382	5670	4616	5220
Daily Catch/vessel	28.9	27.4	30.6	29.9	31.5	25.6	29.0
q	0.00065	0.00062	0.00069	0.00067	0.00071	0.00058	0.00065

Table 3.1: PNA fleet characteristics. Catch in tons.

q value	0.0001	0.0002	0.0003	0.0004	0.0005	0.0006	0.0007	0.0008	0.0009	0.001
Yearly catch/boat	800	1600	2400	3200	4000	4800	5600	6400	7200	8000
Daily catch/boat	4	9	13	18	22	27	31	36	40	44

Table 3.2: Catchability q values and corresponding catch values in tonnes. Based on MSY stock size of 8 million tons, and a 180 day fishing season.

Price per ton (p) of skipjack tuna can be estimated from Thailand frozen imported prices. This is the most representative price measure because 90 percent of skipjack tuna caught in the PNA is loined for canning in Thailand (WCPF 2014). Prices for the period 2010 to 2015 were moderately volatile, ranging from around USD 1,200 to about 2,200 per ton. I will assume p to be USD 1,500 per ton.

Estimates on the operating cost for the PNA fishing fleets are not publicly available. The FFA (2016a) reports that the fuel costs are the most significant and volatile costs for the PNA fleet. Detailed cost estimates for the Ecuadorian purse seine fishing fleets over the 2014-2014 are outlined in Bucaram (2017), which have been used to estimate the cost for the Eastern Pacific Ocean fishing fleets operating in the Antigua Convention Area. For the Ecuadorian fleet the average number of fishing trips per year is 6, with each trip lasting an average of 36 days. This translates into an average of 216 days out at sea. Considering that a fishing day in the PNA excludes travel to the fishing grounds, the fishing characteristics with regards to season length appear to be similar with only 6 days on average difference per trip between the fleets. If these six days are taken to be the travel time to fishing grounds, then we can assume three days travel one way. This is a reasonable assumption (and also a likely an underestimation) since the PNA fishing grounds are geographically large and are far from DWFN countries. Out of the 264 purse seine fishing boats registered in good standing with the FFA for August 2016, the average capacity was 1,100 metric tons. The category with the highest capacity for the Ecuadorian fleet is 1,050 metric tons. The average annual fuel used for vessels in this category is 613,000 gallons or about 1,957 metric tons. The Singapore marine diesel oil (MDO) price index is used by the FFA to estimate the cost of fuel for the PNA fleet FFA (2016a). The average price of diesel over the 2012 to 2014 period was USD 800/mt (FFA 2016a). This means that fuel cost alone for fishing vessels in the PNA is at least USD 1.57 million a year on average. This figure is likely higher due to the PNA having larger vessels in its fleet. Other costs include labor, supplies such as food and fishing gear, and maintenance. Factoring these other costs in, the total cost could potentially be much higher. For tractability I assume that PNA vessels have about USD 2 million a year in total operating cost, with a sensitivity analysis also being provided for this parameter. The catch rate for the Ecuadorian fleet is lower than the PNA fleets. Total catch per year is on average 3,120 tons per vessel compared to 5,220 for the PNA fleet. If we assume 180 fishing days like the PNA this comes in at only around 17 tonnes per day, lower than the 25 tonnes estimated by the FFA for the PNA fleet.

The initial parameters, which I will consider the baseline parameters, for the simulation exercise are $K = 16,000,000$, $r = 0.36$ per year, $q = 0.0006$, $p = 2000$ per ton, $c = 2000000$ per vessel per year, and $\rho = 0.1$. $a = 0.0002$ and $b = 0.0009$. It should be noted that the values of a and b were chosen so as to ensure that $q = \bar{q}$, so that the results can be compared to what happens if the estimate of q is incorrect.

3.3.1 Results

The first question is whether the results from the model provide a reasonable estimation of the PNA fishery. The PNA only harvests up to the MSY of the fishery. Table 2.1 shows that the range of effort days expended in the PNA fishery over the 2010 to the 2015 period range from a low of 36,739 to a high of 50,526 effort days. The predicted optimal effort days in the homogeneous case is 57,081, and heterogeneous model is 45,594. Table 2.3 show that the range of total estimated catch size over 2008 to 2015 is from a low of 1.11 million tons to a high of 1.58 million tons. The predicted optimal catch size in the homogeneous case is 1.44 million tons, and heterogeneous model is also around 1.44 million tons. The optimal stock sizes of 7.54 millions tons for the standard model (Table 3.3) and 7.53 million tons for the heterogeneous case are not dissimilar to the MSY levels of 8 million tons estimates for the PNA (Figure 3.1). Given these results, the estimates appear to be reasonably representative of the PNA fishery.

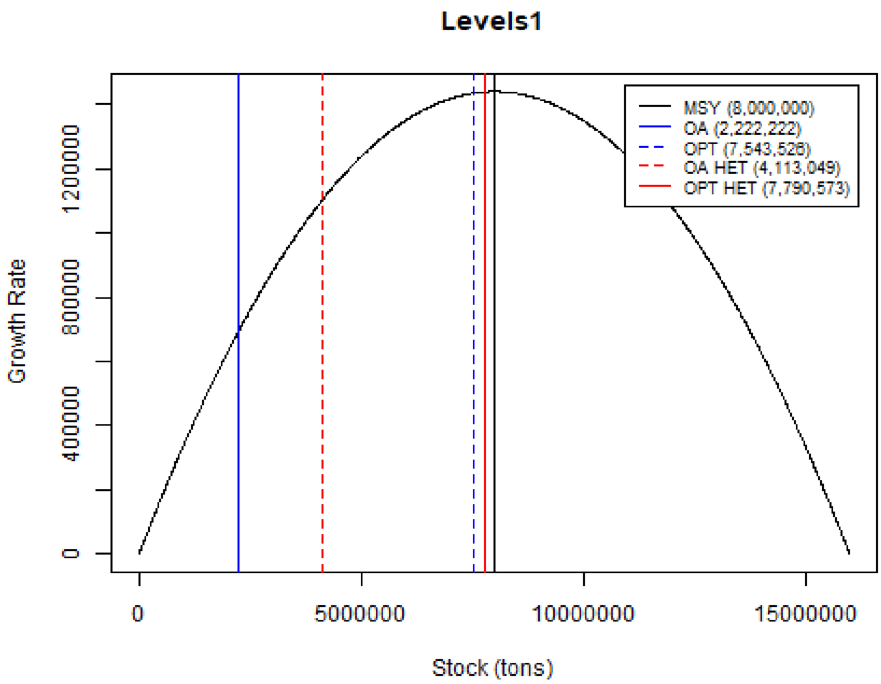


Figure 3.1: MSY, open access and optimal stock levels for both the standard homegenous model and the heterogeneous model. Stock levels for X^* and X_{OA} are similar for both models.

q	X	E	P/day	Rev Input	h	P/ton	Rev Output
0.0002	10,519,439	110,981	6,421	712,643	1,297,180	549.38	712,643
0.0003	9,086,899	93,327	11,606	1,083,164	1,413,420	766.34	1,083,164
0.0004	8,333,333	77,625	16,667	1,293,750	1,437,500	900.00	1,293,750
0.0005	7,791,170	63,934	22,651	1,448,149	1,439,019	1,006.34	1,448,149
0.0006	7,543,526	57,081	26,607	1,518,732	1,435,312	1,058.12	1,518,732
0.0007	7,309,260	50,282	31,526	1,585,207	1,429,265	1,109.11	1,585,207
0.0008	7,130,526	44,902	36,426	1,635,578	1,422,990	1,149.39	1,635,578
0.0009	6,989,534	40,547	41,310	1,675,017	1,417,027	1,182.06	1,675,017
0.0010	6,875,396	36,955	46,184	1,706,708	1,411,543	1,209.11	1,706,708

Table 3.3: Homogeneous case - varying value of q from $0.0002 - 0.001$. (Revenue in 000's)

It should be noted that the results in this section represent the best case scenario for the PNA in extracting rent from the fishing vessels. The result of this is that the license price levels and the corresponding revenue levels should be significantly higher that what is observed in the real world, but not so high that it exceeds the observed catch value. As predicted by the model, revenue in the standard homogeneous model are the same for input and output management schemes (Table 3.3). In the heterogeneous model, as predicted revenue levels were higher in output regulation compared to input regulation. In the baseline case the revenue from input management is about \$1.22 billion, and output management is about \$1.52 billion (Table 3.4, row 4). These results are still under the

a	b	$\bar{q}$	X	E	P/day	Rev Input	h	P/ton	Rev Output
0.0002	0.0006	0.00037	8,528,904	62,478	15,087	942,596	1,433,706	863.82	1,238,465
0.0002	0.0007	0.00044	8,117,597	55,961	18,716	1,047,352	1,439,689	941.22	1,355,059
0.0002	0.0008	0.00052	7,790,573	50,370	22,659	1,141,325	1,439,013	1,006.47	1,448,319
0.0002	0.0009	0.00060	7,531,466	45,594	26,828	1,223,176	1,435,061	1,060.70	1,522,163
0.0002	0.0010	0.00069	7,324,728	41,520	31,155	1,293,562	1,429,740	1,105.68	1,580,831

Table 3.4: Heterogeneous case - holding $a = 0.0002$ constant, and varying b from $0.007 - 0.001$. (Revenue in 000's)

a	b	$\bar{q}$	X	E	P/day	Rev Input	h	P/ton	Rev Output
0.0002	0.0010	0.00069	7,324,728	41,520	31,155	1,293,562	1,429,740	1,105.68	1,580,831
0.0003	0.0010	0.00073	7,241,549	40,890	33,242	1,359,258	1,427,057	1,124.22	1,604,332
0.0004	0.0010	0.00078	7,168,995	40,270	35,265	1,420,127	1,424,462	1,140.62	1,624,768
0.0005	0.0010	0.00082	7,105,227	39,666	37,226	1,476,597	1,421,986	1,155.20	1,642,676
0.0006	0.0010	0.00086	7,048,764	39,081	39,126	1,529,093	1,419,641	1,168.24	1,658,485

Table 3.5: Heterogeneous case - varying a from $0.0002 - 0.0006$, and holding $b = 0.001$ constant. (Revenue in 000's)

a	b	$\bar{q}$	X	E	P/day	Rev Input	h	P/ton	Rev Output
0.0005	0.0006	0.00055	7,704,235	58,651	23,923	1,403,129	1,438,032	1,024.28	1,472,947
0.0004	0.0007	0.00055	7,688,957	53,836	24,159	1,300,630	1,437,823	1,027.46	1,477,303
0.0003	0.0008	0.00057	7,625,960	49,477	25,172	1,245,429	1,436,852	1,040.65	1,495,259
0.0002	0.0009	0.00060	7,531,466	45,594	26,828	1,223,176	1,435,061	1,060.70	1,522,163
0.0001	0.0010	0.00065	7,420,799	42,147	29,009	1,222,651	1,432,452	1,084.58	1,553,608

Table 3.6: Heterogeneous case - increasing the range of a and b from 0.0005 and 0.0006, to 0.0001 and 0.001. (Revenue in 000's)

a	b	$\bar{q}$	X	E	P/day	Rev Input	h	P/ton	Rev Output
0.0001	0.0005	0.00025	9,706,596	68,207	8,899	606,987	1,374,469	667.10	916,903
0.0002	0.0006	0.00037	8,528,904	62,478	15,087	942,596	1,433,706	863.82	1,238,465
0.0003	0.0007	0.00050	7,878,620	54,987	21,477	1,180,925	1,439,669	988.56	1,423,197
0.0004	0.0009	0.00070	7,317,431	44,066	31,329	1,380,561	1,429,517	1,107.29	1,582,896
0.0005	0.0010	0.00082	7,105,227	39,666	37,226	1,476,597	1,421,986	1,155.20	1,642,676

Table 3.7: Heterogeneous case - shifting a and b from 0.0001 and 0.0006, to 0.0005 and 0.001. (Revenue in 000's)

real observed value of the catch in the PNA. The difference is just under \$300 million, or about 24.5 percent of the input management revenue. This result for the baseline was consistent over all other all other combinations of a and b (Table 3.4 - Table 3.7). An interesting feature is that as $\bar{q}$ increases, the difference in input and output revenue in percentage terms falls. The best example is from Table 3.7 where the difference in the revenue in percentage terms falls from around 50 percent in row 1, to just over 10 percent at row 5. This result is also consistent over all examples.

a	b	$\bar{q}$	X	E	p/day	Rev Input	h	p/ton	Rev Output
		0.0005	7,802,722	64,245	22,490	1,444,853	1,439,124	1,004	1,444,853
0.0002	0.0009	0.0006	7,531,466	45,594	26,828	1,223,176	1,435,061	1,061	1,522,163
0.0002	0.0009	0.0005	7,929,054	64,245	20,843	1,339,045	1,957,799	978	1,915,540

Table 3.8: Comparison of homogeneous model with $q = 0.006$ to heterogeneous model with equivalent effort levels.

As $\bar{q}$ increases, optimal stock size X will fall also. $\bar{q}$ increases if either a (Table 11), b (Table 9), or both increase when there shift upward of the distribution and vice versa. When the range of a and b increase in equal measure, the $\bar{q}$ increases also but at a smaller magnitude (Table 13). The effect on the steady state stock level $X*$ is the opposite to that of $\bar{q}$. As predicted, when $\bar{q}$ increases it means only the most productive fishing vessels are fishing which effectively increase the effort and harvest potential which leads to lower equilibrium stock levels. Increases in $\bar{q}$ lead to increases in prices for both input and output management. These changes in the license price levels are expected as creases in $\bar{q}$ mean that the marginal fisher is willing to pay a higher price that those with lower $\bar{q}$.

It is clear that there is a significant difference in the standard model compared to the heterogeneous model. What does this mean for the PNA? In the best case scenario, the PNA correctly estimates the value of q, given the values of a and b. Assuming that it is 0.006, this means there would be an effort level of about 57,081 fishing days at a revenue level of \$1.52 billion. Given the same level of $\bar{q}$ which correspond to $a = 0.0002$ and $b = 0.0009$, the heterogeneous model yields a lower effort level at 45,594 fishing days, with a lower revenue at \$1.22 billion under input regulation. However since the PNA is selling 57,081 effort days, the actual effect given the parameters $a = 0.0002$ and $b = 0.0009$ is that $\bar{q} = 0.0005$, which would yield the actual and slightly higher revenue level of \$1.32 billion under input regulation. The reason why X^* is higher is because the fishery is not yet at equilibrium and $\bar{q}$ is lower. The key takeaway is that under output regulation actual revenue would be significantly higher under output regulation at \$1.78 billion, and even under the standard model revenue would be \$1.51 billion.

What if the estimate that the PNA has is not correct? If q is overestimated, for example if the actual $\bar{q} = 0.0006$ and the PNA estimates a q value of 0.0007, then effort level and harvest are lower. The effect on the stock levels are not significant because stocks will remain in a healthy state. Revenue will fall, so this is not desirable from an income perspective. On the other hand if the PNA underestimates $q = 0.0005$, while actual $\bar{q} = 0.0006$, then the predicted effort levels and harvest levels are going to be higher, resulting in lower stock levels. In this case stock levels may fall lower than expected which may have undesirable consequences for the future sustainability of the fishery. However, in this case revenue levels are going to be higher.

Sensitivity analyses was conducted for parameters K, r, p , and c and are outlined in Appendix B. The results of the sensitivity analyses are consistent with the theoretical predictions in the model.

3.4 Discussion

3.4.1 Policy Implications

The standard model for the single country case predicts that whether licenses are sold as units of harvest under output regulation or days of fishing effort under input regulation, the revenue for the manager is the same. This implies that from a revenue perspective the management scheme does not really matter. The most significant result of the heterogeneous model in the single country case is that the revenues under the two schemes are not equal. Furthermore, the analysis finds that output regulation will generate higher revenues than input regulation. These results strongly suggest that the management scheme adopted is an important determinant of revenue levels, which supports a switch to output regulation from the Vessel Day Scheme. A key consideration on whether a switch to harvest based licenses will be successful, is how well the PNA will be able to monitor harvest levels.

A serious issue for the PNA is the prevalence of illegal and unreported (IUU) fishing. The PNA countries are actively working to improve monitoring and surveillance to reduce IUU fishing. However, the FFA (2016b) report that the majority of IUU fishing activity are from fishing vessels that are licensed to operate in the Pacific region. This has important implications for the VDS as this suggests that stronger measures are required to improve monitoring of fishing vessels and their catch levels. If fishing vessels can continue to fish illegally or under report catch sizes, then a switch to harvest based licenses will not be successful. However, if appropriate monitoring measures are taken, a switch to output regulation will result in higher revenue to the the PNA members. One consequence is that this will directly impact rent for fishing vessels negatively. This will most likely increase the incentive for these licensed vessels to fish illegally, which further emphasizes the importance of monitoring and surveillance.

Turning to a broader perspective on fishery management, one important advantage of the heterogeneous model over the standard model is that it provides more accurate results with respect to the harvest levels of the fishing vessels, and in turn the revenue dynamics of a fishery. This is important for policy makers because if the predictions of the model are incorrect then the best case scenario is that the revenue potential is not realized, and the worst case is that the fishery could collapse from over harvesting. Overall the standard model may be less forgiving of an error in the estimation of the catchability value q as it is a single measure compared to the range of catchability values for heterogeneous model. In addition, since heterogeneity of fishing vessels is a closer representation of the real world, the heterogeneous vessels model provides a more robust representation of a fishery and the dynamics involved.

Another benefit of the heterogeneous model is that it can identify the marginal price that each individual fishing fishing vessels is willing to pay for a license, which is not possible with the standard model. This allows for analysis of different auction mechanisms, and gives policy makers the opportunity to explore benefits or drawbacks of different auction types. Finally, the heterogeneous model can predict which fishing vessels will be able to participate in a fishery, and can be used to explain the phenomenon where small fishermen are driven out of fisheries when new policies are introduced. The standard model is unable to explain this observation. Overall the heterogenenous model gives policy makers additional tools to analyze the impacts of different policies that are possible with the standard model.

3.4.2 Limitations

The first major limitation of the model is the linear production function of the fishing vessels. In the real world, fishing vessels are expected to have an optimal level of effort or harvest, which are a function of the vessel characteristics as well as operating costs. While a linear production function such as this allows for more tractability and simplicity in the model, it does not capture this feature of fishing vessels. Theoretically, the fishing vessels can fish indefinitely with the only limitation being the time and harvest limits placed on the model exogenously. The second primary limitation of the model is the uniform distribution assumption of productivity levels of fishing vessels used in the simulation exercise. Once again the benefits of this assumption are tractability and simplicity in modeling. However, a more real world representation of purse seine fishing vessel productivity functions may be Normal or Pareto distribution functions. The difficulty of these distribution functions is that they may not provide closed form theoretical solutions. Future extension to this study should focus on improving these two primary aspects.

3.5 Conclusion

The motivation for this study is the debate around the Parties to the Nauru Agreement (PNA) tuna coalition, regarding a switch from the current input regulation based Vessel Day Scheme to an output regulation based scheme. There are two primary considerations for the PNA, which are important for most fisheries in general. The first is to maximize the revenue stream generated from the fishery the fishery owner. The second is ensuring the continued sustainability of the fishery into the future. This implies accurate modeling of harvest size to ensure that overfishing does not occur. The primary weakness of VDS is that there are no limits on the amount of fish that can be caught within the time frame provided by the license. The standard Gordon-Schaefer model, which assumes that fishing vessels are homogeneous, predicts that there is no difference in the input or output management schemes. In order to allow for analysis of the two schemes, I introduce into the standard model heterogeneous fishing vessels. The heterogeneous model assumes fishing vessel productivity levels are uniformly distributed. I outlined the model and the theoretical predictions. I then simulated the fishery using estimated parameters, in order to validate the theoretical model.

The main result of this study is that in contrast to the standard model, the heterogeneous model predicts that the revenues from input and output regulation are not the same. The analysis suggests that output regulation yields higher revenues. This result lends support to the argument for switching to an output regulation based scheme over input regulation for a single country. Although this result is important, extension of the model to a multi-country setting is critical for more policy relevance to the PNA.

Relative to the standard model, the heterogeneous model is more representative of the dynamics of a fishery. The heterogeneous model demonstrates that the standard model is less forgiving of an error in the catchability value used, and may lead to an underestimate or overestimate of the harvest level. This is important for fisheries with a large fleet capacity such as the PNA. Underestimation is detrimental to the stock levels, and overestimation yields lower revenue levels. Due to the homogeneity assumption for fishing vessels, the standard model assumes all fishing vessels will try to participate in the fishery and are limited only by the the effort level set by the manager. It provides no mechanism to determine which vessels end up with the limited number of fishing licenses. In contrast, the heterogeneous model endogenously determines which vessels participate in the fishery, which is determined by the productivity levels of the fishing vessels. Two key simplifying assumptions in the model are a linear cost function and a uniform productivity distribution function for the fishing vessels. Future studies can be improved by incorporating a non linear cost function, as well as pareto or normal distribution productivity functions.

Appendix 2

3.A Homogeneous Model - Optimal Extraction

The standard maximization problem for a fishery manager to optimize profit over the lifetime of the fishery is

$$\max_E \int_0^\infty e^{-\rho t}[(ph(X_t, E_t) - cE)]dt$$

subject to

$$\dot{X}_t = g(X_t) - h(X_t, E_t)$$

$$X_0 = \bar{X}, \quad E_0 = \bar{E}, \quad X_t \geq 0, \quad E_t \geq 0$$

To solve this problem, the Hamiltonian equation is

$$H = ph(X_t, E_t) - cE + \lambda_t[g(X_t) - h(X_t, E_t)]$$

Applying the maximum principle, the following conditions are derived

$$\frac{\partial H}{\partial E_t} = ph_E(X_t, E_t) - c - \lambda h_E(X_t, E_t) = 0 \tag{3.36}$$

$$\dot{\lambda} = \lambda\rho - ph_X(X_t, E_t) - \lambda[g_X(X_t) - h_X(X_t, E_t)] \tag{3.37}$$

$$\dot{X} = g(X_t) - h(X_t, E_t) \tag{3.38}$$

The solution to the optimization problem depends on the functional forms used for the growth and harvest functions. Substituting and applying the steady state condition $\dot{X} = 0$, after rearranging the following condition is found.[3]

$$(p - \frac{c}{h_E})\rho = (p - \frac{c}{h_E})g_x + \frac{c}{X_t h_E} g(X_t)$$

After some rearranging, the functional form of the above equation is

$$(\frac{2pr}{K})X^2 - (pr - p\rho - \frac{cr}{qK})X - \frac{\rho c}{q} = 0$$

Applying the quadratic equation, the solution for the optimal stock size X^* can be found. The solution for X^* takes the following form, which can be positive or negative, however the positive root is the solution to the problem in this case and we disregard the negative root.

$$X^* = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A}$$

where

$$A = \frac{2pr}{K}; B = pr - p\rho - \frac{cr}{qK}; C = \frac{\rho c}{q}$$

[3]This is a standard textbook derivation that can be found, for example, in Clark (2010).

Substituting equation 3.9 into the equation of motion for stocks (equation 3.1) yields the optimal equilibrium (steady state) effort level E^*.

$$E^* = \frac{r}{q}(1 - \frac{X^*}{K}) \tag{3.39}$$

3.B Heterogeneous Model - Optimal Extraction

From the harvest function

$$h(X,\bar{q}) = (b^2 - \bar{q}^2)\frac{XeN}{2(b-a)}$$

I find

$$h_{\bar{q}}(X,\bar{q}) = -\bar{q}\frac{XeN}{(b-a)}$$

$$h_X(X,\bar{q}) = (b^2 - \bar{q}^2)\frac{eN}{2(b-a)}$$

From the effort function

$$\bar{E}(\bar{q}) = eN\Big(1 - \frac{\bar{q}-a}{b-a}\Big)$$

I find

$$\bar{E}_{\bar{q}}(\bar{q}) = -eN\Big(\frac{1}{b-a}\Big)$$

From the logistic growth function

$$g(X) = rX(1 - X/K)$$

I find

$$g_x(X) = r - \frac{2rX}{K}$$

From Section 2 the Hamiltonian equation is

$$H = ph(X_t,\bar{q}_t) - cE(\bar{q}_t) + \lambda_t[g(X_t) - h(X_t,\bar{q}_t)]$$

Substituting for the functional forms, the Hamiltonian becomes

$$H = p(b^2 - \bar{q}^2)\frac{XeN}{2(b-a)} - ceN\Big(1 - \frac{\bar{q}-a}{b-a}\Big) + \lambda_t\Big[rX(1-X/K) - (b^2 - \bar{q}^2)\frac{XeN}{2(b-a)}\Big]$$

Applying the maximum principle, the following conditions are derived

$$\frac{\partial H}{\partial \bar{q}} = p(-\bar{q}\frac{XeN}{(b-a)}) - c(-eN\Big(\frac{1}{b-a}\Big)) - \lambda(-\bar{q}\frac{XeN}{(b-a)}) = 0 \tag{3.40}$$

$$\dot{\lambda} = \lambda\rho - p(b^2 - \bar{q}^2)\frac{eN}{2(b-a)} - \lambda[r - \frac{2rX}{K} - (b^2 - \bar{q}^2)\frac{eN}{2(b-a)}] \tag{3.41}$$

$$\dot{X} = rX(1 - X/K) - (b^2 - \bar{q}^2)\frac{XeN}{2(b-a)} \tag{3.42}$$

From MP1

$$\lambda = p - \frac{c}{X_t \bar{q}_t}$$

$$\dot{\lambda} = c\Big[\frac{1}{X_t^2 \bar{q}_t}\frac{dx}{dt} + \frac{1}{X_t \bar{q}_t^2}\frac{dq}{dt}\Big]$$

Substituting into MP2 yields

$$\Big(p - \frac{c}{X_t \bar{q}_t}\Big)\rho = p(b^2 - \bar{q}^2)\frac{eN}{2(b-a)} + \Big(p - \frac{c}{X_t \bar{q}_t}\Big)[r - \frac{2rX}{K} - (b^2 - \bar{q}^2)\frac{eN}{2(b-a)}]$$

Applying the steady state condition $\dot{X} = 0$, the following steady state condition is found.

$$\Big(p - \frac{c}{X_t \bar{q}_t}\Big)\rho = p(r - \frac{rX_t}{K}) - \Big(p - \frac{c}{X_t \bar{q}_t}\Big)[\frac{rX_t}{K}]$$

Rearranging gives

$$(\frac{2pr}{K})X^2 + (p\rho - pr - \frac{cr}{K\bar{q}_t})X - \frac{\rho c}{\bar{q}_t} = 0$$

The solution for $\bar{X}$ takes the following form,

$$\bar{X} = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A}$$

where

$$A = \frac{2pr}{K}; B = p(\rho - r) - \frac{cr}{K\bar{q}_t}; C = \frac{\rho c}{\bar{q}_t}$$

Substituting this into the equation of motion for stocks yields an expression for optimal $\bar{q}$, which together with the equation for stocks determines the solution for the model.

To determine stability, substitute $\frac{dx}{dt} = \dot{x}$ into the expression for $\dot{\lambda}$ and into MP2

$$\frac{dq}{dt} = \Big(\frac{pX_t\bar{q}_t^2}{c} - \bar{q}\Big)\Big[\rho - r + \frac{2rX}{K} + (b^2 + \bar{q}^2)\frac{eN}{2(b-a)}\Big] - \Big(\frac{pX_t\bar{q}_t^2}{c}\Big)\frac{(b^2 - \bar{q}^2)eN}{2(b-a)} - \frac{\bar{q}}{X_t}\Big(rX(1 - X/K) - (b^2 - \bar{q}^2)\frac{XeN}{2(b-a)}\Big) \quad (3.43)$$

Re-arrange to get an expression for $\dot{q}$.

$$\dot{q} = \Big(\frac{pX_t\bar{q}_t^2}{c}\Big)\Big[\rho - r + \frac{2rX}{K}\Big] - \bar{q}\Big[\rho - \frac{rX}{K}\Big] \quad (3.44)$$

$$\dot{X} = \Big(rX - \frac{rX^2}{K}\Big) - (b^2 - \bar{q}^2)\frac{XeN}{2(b-a)}$$

$\dot{X}$ and $\dot{q}$ form the set of Euler equations, which can determine the stability of the system.

$$A = \begin{pmatrix} a & b \\ c & d \end{pmatrix} = \begin{pmatrix} \frac{\partial \dot{X}}{\partial X} & \frac{\partial \dot{X}}{\partial \bar{q}} \\ \frac{\partial \dot{q}}{\partial X} & \frac{\partial \dot{q}}{\partial \bar{q}} \end{pmatrix}$$

At steady state $\dot{X} = \dot{q} = 0$, which then gives us the following conditions

$$\frac{\partial \bar{X}}{\partial X} = r - \frac{2rX}{K} - (b^2 - \bar{q}^2)\frac{eN}{2(b-a)} = 0$$

$$\frac{\partial \bar{X}}{\partial \bar{q}} = (2\bar{q} - b^2)\frac{XeN}{2(b-a)} < 0$$

$$\frac{\partial \dot{q}}{\partial X} = \frac{p\bar{q}_t^2}{c}(\rho - r) + \frac{2pr\bar{q}^2X}{cK} + \frac{r\bar{q}}{K} > 0$$

$$\frac{\partial \dot{q}}{\partial \bar{q}} = \left(\frac{2pX_t\bar{q}_t}{c}\right)\left[\rho - r + \frac{2rX}{K}\right] - \left[\rho - \frac{rX}{K}\right] = 0$$

μ is an eigenvector of A if $\mu^2 + (a+d)\mu + (ad - bc) = 0$.

$$\mu = \frac{(a+d) \pm \sqrt{(a+d)^2 - 4(ad-bc)}}{2(1)}$$

So eigenvectors $\mu_1 > 0$, $\mu_2 < 0$. This means the steady state (at X^* and $\bar{q}^*$) is a saddle point.

3.C System Stability

To check for the stability of the system of equations $\dot{X} = f(X, \bar{q})$ and $\dot{E} = g(X, \bar{q})$), I need to find

$$A \equiv \begin{pmatrix} a & b \\ c & d \end{pmatrix} \equiv \begin{pmatrix} f_x(X^*, \bar{q}^*) & f_{\bar{q}}(X^*, \bar{q}^*) \\ g_x(X^*, \bar{q}^*) & g_{\bar{q}}(X^*, \bar{q}^*) \end{pmatrix}$$

in order to compute the eigenvalues which can identify whether the system is stable. From equation 3.3,

$$(\frac{2pr}{K})X^2 + (p\rho - pr - \frac{cr}{K\bar{q}_t})X - \frac{\rho c}{\bar{q}_t} = 0$$

an expression for $\bar{X}$ takes the following form, where the positive root is the solution.

$$\bar{X} = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A} \tag{3.45}$$

where

$$A = \frac{2pr}{K}; B = p\rho - pr - \frac{cr}{K\bar{q}_t}; C = \frac{\rho c}{\bar{q}_t}$$

Substituting $\bar{X}$ into the equation of motion for stocks yields the optimal equilibrium (steady state) cutoff catchability level $\bar{q}$.

$$\bar{q} = \left[b^2 - \frac{2r(b-a)}{eN} + \frac{2rX(b-a)}{eNK}\right]^{\frac{1}{2}} \tag{3.46}$$

$$\frac{\partial \bar{q}^*}{\partial \bar{q}} = 0$$

$$\frac{\partial \bar{q}^*}{\partial X} = \frac{1}{2}\left[b^2 - \frac{2r(b-a)}{eN} + \frac{2rX(b-a)}{eNK}\right]^{-\frac{1}{2}} \frac{2r(b-a)}{eNK} \tag{3.47}$$

Rearranging the expression for X^* yields

$$\bar{X} = \frac{-(p\rho - pr - \frac{cr}{K\bar{q}_t}) \pm \sqrt{(p\rho - pr - \frac{cr}{K\bar{q}_t})^2 - 4(\frac{2pr}{K})(\frac{\rho c}{\bar{q}_t})}}{2(\frac{2pr}{K})}$$

$$\bar{X} = \frac{\left((p\rho - pr - \frac{cr}{K\bar{q}_t})^2 - 4(\frac{2pr}{K})(\frac{\rho c}{\bar{q}_t})\right)^{\frac{1}{2}}}{(\frac{4pr}{K})} - \frac{(p\rho - pr - \frac{cr}{K\bar{q}_t})}{(\frac{4pr}{K})} \tag{3.48}$$

$$\bar{X} = \frac{\left((p\rho - pr - \frac{cr}{K\bar{q}})^2 - \frac{8cpr\rho}{\bar{q}K}\right)^{\frac{1}{2}}}{(\frac{4pr}{K})} - \frac{Kp\rho}{4pr} + \frac{K}{4} + \frac{c}{4\bar{q}p} \tag{3.49}$$

$$\bar{X} = \Big((p\rho - pr - \frac{cr}{K\bar{q}})^2 - \frac{8cpr\rho}{\bar{q}K}\Big)^{\frac{1}{2}}(\frac{K}{4pr}) - \frac{Kp\rho}{4pr} + \frac{K}{4} + \frac{c}{4\bar{q}p} \tag{3.50}$$

$$\bar{X} = (p\rho - pr - \frac{cr}{K\bar{q}})^2\Big(\frac{K}{4pr}\Big)^2 - \frac{8cpr\rho}{\bar{q}K}\Big(\frac{K}{4pr}\Big)^2 - \frac{Kp\rho}{4pr} + \frac{K}{4} + \frac{c}{4\bar{q}p} \tag{3.51}$$

$$\bar{X} = (p\rho - pr - \frac{cr}{K\bar{q}})^2\Big(\frac{K}{4pr}\Big)^2 - \frac{8cpr\rho}{\bar{q}K}\frac{K^2}{(4pr)^2} - \frac{Kp\rho}{4pr} + \frac{K}{4} + \frac{c}{4\bar{q}p} \tag{3.52}$$

$$\bar{X} = (p\rho - pr - \frac{cr}{K\bar{q}})^2\Big(\frac{K}{4pr}\Big)^2 - \frac{cK\rho}{2\bar{q}pr} - \frac{Kp\rho}{4pr} + \frac{K}{4} + \frac{c}{4\bar{q}p} \tag{3.53}$$

$$\frac{\partial\bar{X}}{\partial X} = 0$$

$$\frac{\partial\bar{X}}{\partial\bar{q}} = (p\rho - pr - \frac{cr}{K\bar{q}})\frac{cK}{8rp^2\bar{q}^2} + \frac{cK\rho}{2pr\bar{q}^2} - \frac{c}{4p\bar{q}^2}$$

After rearranging, the equation of motion for effort $\dot{E}$ is

$$\dot{E} = X\frac{b^2peN}{2(b-a)} - \bar{q}^2X\frac{peN}{2(b-a)} - \Big(\frac{bceN}{b-a}\Big) + \bar{q}\Big(\frac{ceN}{b-a}\Big)$$

and after substituting in $\bar{X}^*$ and $\bar{q}^*$ yields

$$\begin{aligned}
\dot{E} = &\Big[(p\rho - pr - \frac{cr}{K\bar{q}})^2\Big(\frac{K}{4pr}\Big)^2 - \frac{cK\rho}{2\bar{q}pr} - \frac{Kp\rho}{4pr} + \frac{K}{4} + \frac{c}{4\bar{q}p}\Big]\frac{b^2peN}{2(b-a)} \\
-&\Big[\big[b^2 - \frac{2r(b-a)}{eN} + \frac{2rX(b-a)}{eNK}\big]\Big]\Big[(p\rho - pr - \frac{cr}{K\bar{q}})^2\Big(\frac{K}{4pr}\Big)^2 - \frac{cK\rho}{2\bar{q}pr} - \frac{Kp\rho}{4pr} + \frac{K}{4} + \frac{c}{4\bar{q}p}\Big]\frac{peN}{2(b-a)} \\
&- \Big(\frac{bceN}{b-a}\Big) + \Big[\big[b^2 - \frac{2r(b-a)}{eN} + \frac{2rX(b-a)}{eNK}\big]^{\frac{1}{2}}\Big]\Big(\frac{ceN}{b-a}\Big)
\end{aligned} \tag{3.54}$$

Similarly, the equation of motion for stock size is

$$\dot{X} = Xr - X^2\frac{r}{K} - X\frac{b^2eN}{2(b-a)} + \bar{q}^2X\frac{eN}{2(b-a)}$$

and after substitution of $\bar{X}^*$ and $\bar{q}^*$ yields

$$\begin{aligned}
\dot{X} = &\Big[(p\rho - pr - \frac{cr}{K\bar{q}})^2\Big(\frac{K}{4pr}\Big)^2 - \frac{cK\rho}{2\bar{q}pr} - \frac{Kp\rho}{4pr} + \frac{K}{4} + \frac{c}{4\bar{q}p}\Big]r - \\
&\Big[(p\rho - pr - \frac{cr}{K\bar{q}})^2\Big(\frac{K}{4pr}\Big)^2 - \frac{cK\rho}{2\bar{q}pr} - \frac{Kp\rho}{4pr} + \frac{K}{4} + \frac{c}{4\bar{q}p}\Big]^2\frac{r}{K} - \\
&\Big[(p\rho - pr - \frac{cr}{K\bar{q}})^2\Big(\frac{K}{4pr}\Big)^2 - \frac{cK\rho}{2\bar{q}pr} - \frac{Kp\rho}{4pr} + \frac{K}{4} + \frac{c}{4\bar{q}p}\Big]\frac{b^2eN}{2(b-a)} \\
+&\Big[(p\rho - pr - \frac{cr}{K\bar{q}})^2\Big(\frac{K}{4pr}\Big)^2 - \frac{cK\rho}{2\bar{q}pr} - \frac{Kp\rho}{4pr} + \frac{K}{4} + \frac{c}{4\bar{q}p}\Big]\Big[b^2 - \frac{2(b-a)}{eN}(r - \frac{rX^*}{K})\Big]\frac{eN}{2(b-a)}
\end{aligned}$$

The partial derivatives of these are

$$f_x(X^*,\bar{q}^*) \quad = \quad \frac{r}{K}\Big[(p\rho \; - \; pr \; - \; \frac{cr}{K\bar{q}})^2\Big(\frac{K}{4pr}\Big)^2 \; - \; \frac{cK\rho}{2\bar{q}pr} \; - \; \frac{Kp\rho}{4pr} \; + \; \frac{K}{4} \; + \; \frac{c}{4\bar{q}p}\Big]$$

$$\begin{aligned}
f_{\bar{q}}(X^*,\bar{q}^*) &= \Big[(p\rho - pr - \frac{cr}{K\bar{q}})\frac{cK}{8rp^2\bar{q}^2} + \frac{cK\rho}{2pr\bar{q}^2} - \frac{c}{4p\bar{q}^2}\Big]r \\
&-\Big[(p\rho - pr - \frac{cr}{K\bar{q}})^2\Big(\frac{K}{4pr}\Big)^2 - \frac{cK\rho}{2\bar{q}pr} - \frac{Kp\rho}{4pr} + \frac{K}{4} + \frac{c}{4\bar{q}p}\Big]\Big[(p\rho - pr - \frac{cr}{K\bar{q}})\frac{cK}{8rp^2\bar{q}^2} + \frac{cK\rho}{2pr\bar{q}^2} - \frac{c}{4p\bar{q}^2}\Big]\frac{2r}{K} \\
&- \Big[(p\rho - pr - \frac{cr}{K\bar{q}})\frac{cK}{8rp^2\bar{q}^2} + \frac{cK\rho}{2pr\bar{q}^2} - \frac{c}{4p\bar{q}^2}\Big]\frac{b^2eN}{2(b-a)} \\
&+ \Big[(p\rho - pr - \frac{cr}{K\bar{q}})\frac{cK}{8rp^2\bar{q}^2} + \frac{cK\rho}{2pr\bar{q}^2} - \frac{c}{4p\bar{q}^2}\Big]\Big[b^2 - \frac{2(b-a)}{eN}(r - \frac{rX^*}{K})\Big]\frac{eN}{2(b-a)}
\end{aligned}$$

$$\begin{aligned}
g_x(X^*,\bar{q}^*) &= -(\frac{pr}{K})\Big[(p\rho - pr - \frac{cr}{K\bar{q}})^2\Big(\frac{K}{4pr}\Big)^2 - \frac{cK\rho}{2\bar{q}pr} - \frac{Kp\rho}{4pr} + \frac{K}{4} + \frac{c}{4\bar{q}p}\Big] \\
&+ \Big(\Big[b^2 - \frac{2r(b-a)}{eN} + \frac{2rX(b-a)}{eNK}\Big]^{-\frac{1}{2}}\frac{r(b-a)}{eNK}\Big)\Big(\frac{ceN}{b-a}\Big)
\end{aligned}$$

$$\begin{aligned}
g_{\bar{q}}(X^*,\bar{q}^*) &= \Big[(p\rho - pr - \frac{cr}{K\bar{q}})\frac{cK}{8rp^2\bar{q}^2} + \frac{cK\rho}{2pr\bar{q}^2} - \frac{c}{4p\bar{q}^2}\Big]\frac{b^2peN}{2(b-a)} \\
&- \Big[(p\rho - pr - \frac{cr}{K\bar{q}})\frac{cK}{8rp^2\bar{q}^2} + \frac{cK\rho}{2pr\bar{q}^2} - \frac{c}{4p\bar{q}^2}\Big]\Big[b^2 - \frac{2r(b-a)}{eN} + \frac{2rX(b-a)}{eNK}\Big]\frac{peN}{2(b-a)}
\end{aligned}$$

3.D Comparative Statics

In the heterogeneous model I look at the effect of the catchability distribution on stock level $\bar{X}$. To do this I let $a = \alpha b$ where $0 < \alpha < 1$. A change in b moves the whole distribution, while a change in α moves only a. From 3.46 and 3.52 let

$$F(\bar{q}, \bar{X}, b, \alpha) = \bar{X} - \frac{-(p\rho - pr - \frac{cr}{K\bar{q}}) + \sqrt{(p\rho - pr - \frac{cr}{K\bar{q}})^2 - 4(\frac{2pr}{K})(\frac{\rho c}{\bar{q}})}}{2(\frac{2pr}{K})} = 0$$

$$Q(\bar{q}, \bar{X}, b, \alpha) = \bar{q} - \left[b^2 - \frac{2(b - \alpha b)}{eN}(r - \frac{rX^*}{K})\right]^{\frac{1}{2}} = 0$$

Then by linearization, the implicit function theorem, and Cramer's rule we have

$$\frac{\partial \bar{X}}{\partial b} = -\frac{\begin{vmatrix} \frac{\partial F}{\partial \bar{q}} & \frac{\partial F}{\partial b} \\ \frac{\partial Q}{\partial \bar{q}} & \frac{\partial Q}{\partial b} \end{vmatrix}}{\begin{vmatrix} \frac{\partial F}{\partial \bar{q}} & \frac{\partial F}{\partial \bar{X}} \\ \frac{\partial Q}{\partial \bar{q}} & \frac{\partial Q}{\partial \bar{X}} \end{vmatrix}} = -\frac{(\frac{\partial F}{\partial \bar{q}}\frac{\partial Q}{\partial b} - \frac{\partial Q}{\partial \bar{q}}\frac{\partial F}{\partial b})}{(\frac{\partial F}{\partial \bar{q}}\frac{\partial Q}{\partial \bar{X}} - \frac{\partial Q}{\partial \bar{q}}\frac{\partial F}{\partial \bar{X}})} < 0$$

$$\frac{\partial \bar{q}}{\partial b} = -\frac{\begin{vmatrix} \frac{\partial F}{\partial b} & \frac{\partial F}{\partial \bar{X}} \\ \frac{\partial Q}{\partial b} & \frac{\partial Q}{\partial \bar{X}} \end{vmatrix}}{\begin{vmatrix} \frac{\partial F}{\partial \bar{q}} & \frac{\partial F}{\partial \bar{X}} \\ \frac{\partial Q}{\partial \bar{q}} & \frac{\partial Q}{\partial \bar{X}} \end{vmatrix}} = -\frac{(\frac{\partial F}{\partial b}\frac{\partial Q}{\partial \bar{X}} - \frac{\partial Q}{\partial b}\frac{\partial F}{\partial \bar{X}})}{(\frac{\partial F}{\partial \bar{q}}\frac{\partial Q}{\partial \bar{X}} - \frac{\partial Q}{\partial \bar{q}}\frac{\partial F}{\partial \bar{X}})} > 0$$

$$\frac{\partial \bar{X}}{\partial \alpha} = -\frac{\begin{vmatrix} \frac{\partial F}{\partial \bar{q}} & \frac{\partial F}{\partial \alpha} \\ \frac{\partial Q}{\partial \bar{q}} & \frac{\partial Q}{\partial \alpha} \end{vmatrix}}{\begin{vmatrix} \frac{\partial F}{\partial \bar{q}} & \frac{\partial F}{\partial \bar{X}} \\ \frac{\partial Q}{\partial \bar{q}} & \frac{\partial Q}{\partial \bar{X}} \end{vmatrix}} = -\frac{(\frac{\partial F}{\partial \bar{q}}\frac{\partial Q}{\partial \alpha} - \frac{\partial Q}{\partial \bar{q}}\frac{\partial F}{\partial \alpha})}{(\frac{\partial F}{\partial \bar{q}}\frac{\partial Q}{\partial \bar{X}} - \frac{\partial Q}{\partial \bar{q}}\frac{\partial F}{\partial \bar{X}})} > 0$$

$$\frac{\partial \bar{q}}{\partial \alpha} = -\frac{\begin{vmatrix} \frac{\partial F}{\partial \alpha} & \frac{\partial F}{\partial \bar{X}} \\ \frac{\partial Q}{\partial \alpha} & \frac{\partial Q}{\partial \bar{X}} \end{vmatrix}}{\begin{vmatrix} \frac{\partial F}{\partial \bar{q}} & \frac{\partial F}{\partial \bar{X}} \\ \frac{\partial Q}{\partial \bar{q}} & \frac{\partial Q}{\partial \bar{X}} \end{vmatrix}} = -\frac{(\frac{\partial F}{\partial \alpha}\frac{\partial Q}{\partial \bar{X}} - \frac{\partial Q}{\partial \alpha}\frac{\partial F}{\partial \bar{X}})}{(\frac{\partial F}{\partial \bar{q}}\frac{\partial Q}{\partial \bar{X}} - \frac{\partial Q}{\partial \bar{q}}\frac{\partial F}{\partial \bar{X}})} < 0$$

where

$$\frac{\partial F}{\partial \bar{q}} = \frac{cr}{4prK\bar{q}^2} - \frac{K}{8pr} + \frac{1}{2}\Big((p\rho - pr - \frac{cr}{K\bar{q}})^2 - 4(\frac{2pr}{K})(\frac{\rho c}{\bar{q}})\Big)^{-\frac{1}{2}} 2(p\rho - pr - \frac{cr}{K\bar{q}})4\frac{cr}{K\bar{q}^2} + \frac{8pr\rho c}{K\bar{q}^2} > 0$$

$$\frac{\partial F}{\partial \bar{X}} = 1, \qquad \frac{\partial F}{\partial b} = 0, \qquad \frac{\partial F}{\partial \alpha} = 0$$

$$\frac{\partial Q}{\partial \bar{X}} = -\frac{1}{2}\left[b^2 - \frac{2(b - \alpha b)}{eN}(r - \frac{r\bar{X}}{K})\right]^{-\frac{1}{2}} \frac{2(b - \alpha b)}{eN}\frac{r}{K} > 0$$

$$\frac{\partial Q}{\partial \alpha} = -\frac{\alpha b}{eN}(r - \frac{rX^*}{K}) < 0, \qquad \frac{\partial Q}{\partial \bar{q}} = 1$$

$$\frac{\partial Q}{\partial b} = -2b - \frac{2 + 2\alpha}{eN}(r - \frac{rX^*}{K}) > 0$$

The results appear to be be intuitive. The effect of shifting the entire distribution up is that equilibrium stock levels will be lower because of higher harvest potential, and a higher cutoff catchability value. The effect of moving the value of $a = \alpha b$ up is that some fishermen are excluded so harvest potential is lower, and (in relative terms) the cutoff catchability level will decrease.

3.E Sensitivity Analysis

K	$\bar{q}$	X	E	P/day	Rev Input	h	P/ton	Rev Output
14,000,000	0.00060	6,405,494	47,018	31,255	1,469,515	1,250,912	1,475.47	1,845,678
15,000,000	0.00059	6,781,549	47,611	33,452	1,592,681	1,337,612	1,501.33	2,008,199
16,000,000	0.00059	7,156,301	48,142	35,641	1,715,825	1,423,984	1,524.68	2,171,117
17,000,000	0.00058	7,529,919	48,621	37,822	1,838,941	1,510,072	1,545.87	2,334,368
18,000,000	0.00058	7,902,543	49,055	39,997	1,962,024	1,595,912	1,565.19	2,497,903

Table 3.9: Heterogeneous case - varying carrying capacity K from $14,000,000 - 18,000,000$ tons. (Revenue in 000's)

p	$\bar{q}$	X	E	P/day	Rev Input	h	P/ton	Rev Output
1,600	0.00060	7,440,267	46,207	28,604	1,321,706	1,432,951	1,152.37	1,651,288
1,800	0.00059	7,284,538	47,263	32,135	1,518,783	1,428,483	1,337.53	1,910,634
2,000	0.00059	7,156,301	48,142	35,641	1,715,825	1,423,984	1,524.68	2,171,117
2,200	0.00058	7,048,731	48,886	39,128	1,912,795	1,419,639	1,713.43	2,432,458
2,400	0.00058	6,957,121	49,525	42,598	2,109,676	1,415,529	1,903.50	2,694,463

Table 3.10: Heterogeneous case - varying price per ton p from $1,600 - 2,400$ tons. (Revenue in 000's)

c	$\bar{q}$	X	E	P/day	Rev Input	h	P/ton	Rev Output
1,600,000	0.00058	6,916,210	49,811	35,463	1,766,466	1,413,571	1,599.17	2,260,536
1,800,000	0.00058	7,037,835	48,962	35,563	1,741,207	1,419,170	1,561.04	2,215,386
2,000,000	0.00059	7,156,301	48,142	35,641	1,715,825	1,423,984	1,524.68	2,171,117
2,200,000	0.00059	7,271,867	47,350	35,700	1,690,368	1,428,071	1,489.91	2,127,699
2,400,000	0.00060	7,384,760	46,582	35,741	1,664,878	1,431,483	1,456.61	2,085,106

Table 3.11: Heterogeneous case - varying vessel operating cost c from $1,600,000 - 2,400,000$. (Revenue in 000's)

r	$\bar{q}$	X	E	P/day	Rev Input	h	P/ton	Rev Output
0.10	0.00079	3,508,626	16,607	19,779	328,474	273,922	1,280.60	350,785
0.20	0.00071	5,686,472	28,763	33,975	977,206	733,095	1,507.11	1,104,857
0.36	0.00059	7,156,301	48,142	35,641	1,715,825	1,423,984	1,524.68	2,171,117
0.38	0.00057	7,276,048	50,692	35,087	1,778,627	1,507,552	1,518.98	2,289,945
0.40	0.00055	7,389,293	53,273	34,433	1,834,323	1,590,676	1,512.07	2,405,214

Table 3.12: Heterogeneous case - varying intrinsic growth rate r from $0.1 - 0.4$. (Revenue in 000's)

Chapter 4

Heterogeneous Fishing Vessel Model: Multi-country Analysis

4.1 Introduction

The overall goal of this study is to compare an input regulation fishery management scheme to a quota based management scheme, for a cooperatively owned and managed fishery. Standard approaches to modeling this problem based on homogeneous fishing agents predicts an identical outcome for both input and output management schemes, and so meaningful comparisons cannot be made. In order to overcome this issue, I extend the standard modeling techniques through the introduction of heterogeneous fishing agents. The primary variables for comparison are the stock levels, harvest size, rent levels, and the revenue levels to each country.

One clear implication of including heterogeneous fishing agents in this multi-country setting, is that in order to correctly characterize the dynamics of the fishery each individual fishing vessel's incentives have to be accounted for. Profit levels are the most important consideration for fishing vessels, and so license prices are the primary mechanism through which the fishery manager can influence fishing vessels. I consider two price setting methods for both input and output regulation, and I examine whether the target stock, harvest, and revenue levels set by the manager can be achieved in each of these cases. This study demonstrates that multi-patch management is more complex that previously thought, and that the management scheme employed is critically important to achieving the goals of the fishery manager.

With the standard Gordon-Smith model by Gordon (1954) and Smith (1968), fishing vessel catchability value q is always assumed to be constant. This means that all vessels are treated as homogeneous. However, in practice even fishing vessels that are physically identical can be heterogenous with respect to the amount of fish that they catch. This characteristic can be explained by captains and crew with good experience and skill, who can consistently guide the fishing vessels to productive fishing grounds. The main limitation of the standard model is that it predicts that input and output regulation result in the same harvest and revenue levels, and so an alternative methodology for evaluating and comparing each management scheme is required. Previously in Chapter 3, I introduced heterogeneous fishing vessels into the standard Gordon-Smith model for a single country. This model predicted different outcomes between the two approaches, and showed that revenue under output regulation was higher. Although this result was important, it provides limited insights into cooperative management with two or more countries.

An important strand of the literature expanding on the Gordon-Smith model takes into account the spatial aspect of fishery management, incorporating the behavior and movement of fish stocks. Sanchirico and Wilen (1999) developed a model of spatially connected fish stocks, congregated across space in patches. These patches can belong to or represent different countries, and can have different characteristics making them heterogeneous. This model has been especially useful in modelling trans-boundary and straddling fish stocks. In this paper I introduce heterogeneous fishing vessels into the multi-patch model by Sanchirico and Wilen, extending the model and allowing for multi-country analysis not possible with the single country country case.

I limit the analysis to the two patch case, which can be viewed as two neighboring countries, with possible inter-migration of fish stocks. Fishing vessels decide which country to buy licenses from, and licenses can be used only in the country where it was bought. I assume perfect competition in the license market as this reduces the complexity of the analysis, while still allowing key aspects of the model to be considered. I also assume that the fishery manager has incomplete information about the fishing vessels. This assumption reflects conditions in the real world, and increases the scope and contribution of the analysis. In order to provide a benchmark for comparison, I include the standard textbook model from Gordon-Smith and Sanchirico and Wilen. First I outline the model, and characterize conditions for open access and optimal extraction. I then outline the theoretical predictions and consequences of the model, and provide an illustration for two countries.

In this multi heterogeneous country setting, the complexity involved in characterizing equilibrium conditions increases substantially with the inclusion of heterogeneous fishing agents. The most significant challenge is to determine how fishing vessels order themselves over the two countries. This is important because it sets the harvest levels in each patch, which is vital for maintaining the correct stock levels. To characterize this ordering, I examine the profit functions of the fishing vessels and compare them across patches. I show that in this multi-country setting, fishing vessels incentives do not necessarily align with the goals of the fishery manager, and that these incentives differ under input and output regulation. This means that in order to correctly incentivize fishing vessels, careful consideration has to be given to how prices are set under each management scheme.

In this model, the method used to sets prices is dependent on how the harvest function is characterized and entered into the maximization problem. In the single country version of this model, only the most productive fishing vessels can afford to pay for the licenses. The equilibrium price was based on a single cutoff catchability value of the marginal fisher who makes zero profit. Fishing vessels below the marginal fisher cannot afford the licenses and fishing vessels above the marginal fisher make positive rent. In this multi-country scenario the fishery manager can set prices for both countries using a single cutoff value, or it can use individual cutoff values for each country to set corresponding license prices. I call the single cutoff method the full overlap case because in the characterization of the harvest function by the fishery manager, all fishing vessels above the single $\bar{q}$ are allowed to buy licenses in either country. I call the case with individual cutoff catchability levels full separation because in the characterization of the harvest function by the fishery manager, the most productive fishing vessels are assigned to the larger country, and the least productive fishing vessels to the smaller country. In this case, fishing vessels are clearly separated into each country by the productivity levels of the marginal fishers.

In order to determine the optimal management scheme, I use two conditions to examine input and output regulation under both full separation and full overlap price setting methods. The first condition is that the license market has to clear. That is, fishing vessels have an incentive to buy all of the licenses at the given prices. I show that although this condition may appear straightforward, it is not easy to achieve without the assumption of perfect information for the manager. The second and stronger condition, is that fishing vessels efficiently order themselves over the two countries according to their productivity levels. This conditions implies that the most productive fishing vessels buy licenses from the country with the most productive fishery, and the less productive fishing vessels buy licenses from the country with the less productive fishery. If both conditions are met, the scheme is considered supportable in the sense that each country will achieve the predicted harvest, stock and revenue levels. If the first condition is not met then that management scheme is not supportable, and so evaluating the second condition does not matter. If the first condition is met but the second condition is not, then full efficiency is not supported. This means that the fishery manager cannot be certain about where each fishing vessel may decide to fish, and so this implies that the harvest levels predicted by the manager may not be met.

This study has four primary results from the theoretical prediction of the model. First, under input regulation the license market will clear under the full overlap case. However, an efficient ordering of fishing vessels over the two countries is not guaranteed. Second, full efficiency is possible for input regulation under full separation, but this result may be achievable only under specific conditions. Third, output regulation under full overlap is not supportable under the assumptions made in this study. Finally, output regulation under full separation could theoretically achieve the market clearing condition and efficient ordering condition. However, this is unlikely to occur without intervention from the manager and requires the assumption of perfect information. The last two results are strong because they suggest that output regulation is not feasible. However these results are driven by the assumption of constant cost over both countries. If this assumption is relaxed, then output regulation could be supportable under both full separation and full overlap conditions.

The simulation provided in this study is based loosely on parameters from the PNA and the Ecuadorian fishing fleet. The Ecuadorian fleet was used because cost estimates for the PNA fleet are not publicly available. The purpose of the simulation is to demonstrate how the model works, and not intended to draw any PNA specific conclusions. However, the general results of the simulation should be able to provide some insights for policy makers. I assume there are no flows of stocks between countries in these simulations as fewer variables focuses the results, allowing for a clearer interpretation of the key aspects under consideration. Although a simulation based on the standard model is provided, the results are not new. For this reason I focus discussion of the results on the new model. The simulation was split into full overlap and full separation price setting methods. Input and output regulation were then compared under each.

The first result from the simulation is that both full overlap and full separation yield the same harvest rate, steady state stock levels, and total combined rent and effort levels. However, the distribution of rent and effort to each country are different for each approach. In full overlap, each country is weighted the same in terms of the share of rent and effort. This means that if the two countries are the same size they receive the same rent and effort levels. In full separation, one country (call it Country i) is always assigned the most productive fishing vessels through the harvest function even if they are the same size. Country i will receive less effort and subsequently less licenses since fishing vessels assigned to it require less effort to catch the same harvest level as the less productive fishing vessels assigned to other country (call it Country j). Assuming fishing vessels pay the marginal fishing vessels price, Country i will receive higher revenue levels relative to Country j.

The simulation also suggest that potential revenue under output regulation is higher relative to input regulation. This is true for all cases under the heterogeneous model. This result extends from and reinforces the same result from the single country case. However, in this multi-country setting one additional consideration is whether each regulation scheme is supportable. To check this I examine the simulation of fishing vessels profit functions, which largely reflect the predictions of the theoretical model. The simulation results show that input regulation under the full overlap case allows the market to clear, but efficient ordering is not guaranteed. Input regulation under full separation can achieve both efficiency conditions, but this will occur only under specific conditions. Output regulation on the other hand may not achieve the market clearing condition under both full overlap and full separation, and efficient ordering is not possible at all under full overlap. Finally, the simulation suggest that if the two countries are sufficiently different in size, then it may not be able to sell any of its licenses.

The primary contribution of this paper is that it examines the welfare problem for a revenue maximizing fishery coalition, comparing input versus output based regulation. This analysis is not possible with the homogeneous assumption used in the standard models found in the literature, and is achieved by introducing heterogeneity into the multi patch bio-economic model. This study reveals that analysis of input versus output regulation is more complicated than previously thought. While the assumption of heterogeneous fishermen is not new, the motivating problem for this analysis is also novel. To the author's knowledge, the specific problem of the PNA fishery outlined in this multi-country context has yet to be explored within the literature. The potential impacts of such an analysis on policy could be significant for the member countries of the PNA. These results could also have wider implications for fishery management in general, as a large majority of the work done in this field are still based on the simple homogeneous fishing vessels assumption.

A weakness of the analysis is that the linear profit function assumption plays an important role in the results. This assumption implies that profit levels in output regulation are dependent only on stock size and license prices, not productivity. This implies that fishing vessels with a higher productivity level have no advantage under output regulation. Coupled with the constant cost assumption, this somewhat limits the analysis that the model can be applied to. Fortunately these modifications can be made fairly easily, and will be areas for improvement in the future. Another possible criticism could be the simplification of the multi-unit auction mechanism used to allocate licenses in practice, to the perfect competition assumption used in this study. However, auctions are notoriously difficult to implement correctly in practice, and are sensitive to a variety of factors. The multi-country setting and competition between members in the PNA would increase the complexity of such an analysis significantly. In addition,details of the exact mechanism used by the PNA is not available, and so any attempt at replication would also have been an approximation at best. For these reasons examination of the multi-unit auction mechanism used to allocate licenses in the PNA deserves to be examined separately, before being included in this analysis.

The paper is organized as follows. Section 4.2 outlines the model. Section 4.3 provides a numerical illustration of the model. Section 4.4 provides a discussion of the policy implications, and Section 4.5 concludes.

4.2 Model

Assume there are m possible countries with individual stocks of tuna which grow according to a logistic function. Although each stock may have differing characteristic such as growth rate and carrying capacity, I assume for tractability that both stocks share the same growth characteristics, but different carrying capacities. The two countries are neighbors, and there are possible inter-migration between the tuna stocks of each country. These countries sell fishing licenses which allows fishing vessels to operate in their waters. Licenses are country specific and cannot be resold or transferred. There is a fishing fleet of size N which can buy fishing licenses from both countries. In the standard model, fishing vessels are homogeneous. In the hetereogenous fishing vessels model, fishing vessels have a productivity value measured by the catchability coefficient q which is distributed according to some function $f(.)$. As a result the licenses have different values unique to each fishing vessel which depend on how much fish each vessel can catch. The abundance of the fish in a particular country is approximated by the stock size X. I assume that the information on the abundance of fish across countries is common information. This means that the value each vessel places on a license will depend on its own productivity. As fishing vessels catch fish, they deplete the fish stock. I assume that the licenses are all sold at the beginning of the season, which implies that there is significant demand in the market from a high number of N fishing vessels.

In the real world, fishermen are not exactly sure where the fish are going to be. They have some information based on previous experience and forecasting about the probability that fish will be at a certain country at a certain time. I assume that fishing vessels only use the stock level at the beginning of the season as an indication of the profitability of a particular patch. More productive fishing vessels will catch more fish, and so they have a higher valuation of a given license day, relative to a less productive fishing vessel.

For reference, the standard multiple patch model by Sanchirico and Wilen (1999) outlining open access, maximum sustainable yield and optimal extraction equilibrium conditions is outlined in Appendix 4.A. I extend that model by introducing heterogeneous fishing vessels, which follows from the single patch model outlined in Chapter 3, Section 3.2.

Subsection 4.2.1 characterizes the general model, outlines the equilibrium conditions required for open access, and outlines the maximization problem and equilibrium conditions for the optimal extraction solution. In Section 4.2.2, I examine the fishing vessels problem to determine how fishing vessels order or sort themselves over the two countries in equilibrium. This is an important consideration in determining the revenue to each country from the sale of licenses. Examining the fishing vessels profit functions also determines if input or output regulation is supportable.

4.2.1 Heterogeneous Fishing Vessels Model

A critical assumption in the standard model is that fishing vessels are heterogeneous. However in reality, some vessels can catch more than others, even if fishing vessels are physically identical in every way. This is known as the 'good captain' effect, and refers to captains and crew who can consistently guide the fishing vessel to productive grounds. This means that there is an element of heterogeneity in the catchability coefficient of fishing vessels. It follows that the optimal harvest rate calculated using the standard method outlined in Appendix 4.A could be different from the predicted harvest size, as it does not take into consideration the potential variation in harvest rates.

The approach used to determine the number of licenses to be sold for either input or output regulation is similar to the standard model. First, the fishery manager has to find the stock level that corresponds to the management goal. This stock level is then used to find the harvest and effort levels for each regulation scheme, which is then used to determine the number of licenses to sell. Under input regulation the licenses are sold as effort days, and under output regulation licenses are sold by tonnes of tuna caught.

A representative fishing vessel pays a fee to fish over one season only. By backward induction, it's dominant strategy is to extract as much fish as possible. Assume that there is a continuum of N fishing vessels from $q_{min} = a$ to $q_{max} = b$. All fishing vessels are identical aside from the catchability value q. This catchability value q is distributed according to some probability density function $f(.)$ which determines the productivity of the fishing vessels. Let e represent the effort level of a single fishing vessel measured in days, which can vary from 0 to e_{max}, where e_{max} is the total possible number of days in a fishing season. I maintain the constant market price p of tuna assumption, and so each vessel has incentive to fish the maximum number of days in a fishing season due to the linear profit function. All the licenses are sold at the beginning of the season, which implies that each fisherman will only fish in one patch.

If all fishing vessels are allowed to participate in the fishery, total harvest for time t for two countries i and j, can be found by summing the harvest level for all fishing vessels from productivity level a to b. Maintaining the Schaefer (1957) catch-effort relation for the harvest function from the standard model in Appendix 4.A, total harvest at time t is

$$h = N \int_a^b \Big(qX_i e + qX_j e\Big) f(q) dq \tag{4.1}$$

If the fishery is regulated according to some management goal such as MSY or optimal extraction, assuming a sufficiently large fishing fleet, not all fishing vessels will be able to participate. Following from Chapter 3, I define $\bar{q}$ as the productivity level of the least productive fishing vessel who is able to participate in the fishery, which I call the marginal fisher. Suppose that licenses are sold or distributed to fishing vessels according to some competitive allocation method based on the fishing vessels marginal value for the licenses. Then the profit level of the marginal fisher will be equal to zero, and $\bar{q}$ determines the equilibrium price w of the licenses for each country. It follows that only vessels with a catchability coefficient $\bar{q}$ and higher are able to pay the equilibrium price $\bar{w}$ for each respective country, and are the only vessels able to acquire licenses to fish.

The actual harvest level can be found by substituting $\bar{q}$ into the bounds of the harvest function in 4.1. There are two ways the manager can optimize over the two countries. The first approach is to maximize over both countries, resulting in a single value for $\bar{q}$. I refer to this as the full overlap approach because the catchability coefficient $\bar{q} = \bar{q}_i = \bar{q}_j$. This implies that maximizing as a single country will use a single $\bar{q}$ in the bounds for the harvest function. The second approach is to maximize over the two countries separately, resulting in separate $\bar{q}_i$ and $\bar{q}_j$. I refer to this as the full separation case, and implies that maximizing over individual countries will use $\bar{q}_i$ and $\bar{q}_j$ as bounds in the harvest function. Section 4.2.1 outlines how this is achieved.

The level of actual effort expended $\bar{E}$ is also a function of $\bar{q}$. To see this, define the total number of vessels who can bid for licenses as the potential effort level

$$E = eN$$

As the fishing vessels with $\bar{q} \leq q \leq q_{max}$ are the only vessels able to buy licenses to fish, this means actual effort expended is E multiplied by the probability of $\bar{q} \leq q \leq q_{max}$. Maintaining the assumption that q has some distribution $f(.)$ from $q_{min} = a$ to $q_{max} = b$, the expressions for total actual effort are as follows. For the full overlap case, 4.2 and 4.3 can apply.

$$\bar{E}_i = eN_i Pr[\bar{q}_i \leq q \leq b] = eN_i \int_{\bar{q}_i}^{b} f(q)dq \tag{4.2}$$

$$\bar{E}_j = eN_j Pr[\bar{q}_j \leq q \leq b] = eN_j \int_{\bar{q}_j}^{b} f(q)dq \tag{4.3}$$

For the full separation case, assuming that $\hat{q}_i \geq \bar{q}_j$, 4.4 and 4.5 apply.

$$\bar{E}_i = eN_i Pr[\bar{q}_i \leq q \leq b] = eN_i \int_{\bar{q}_i}^{b} f(q)dq \tag{4.4}$$

$$\bar{E}_j = eN_j Pr[\bar{q}_j \leq q \leq \bar{q}_i] = eN_j \int_{\bar{q}_j}^{\bar{q}_i} f(q)dq \tag{4.5}$$

The equations of motion for stocks are

$$\dot{X}_i = g(X_i) - h(X_i, \bar{q}_i) - d_i X_i + d_j X_j \tag{4.6}$$

$$\dot{X}_j = g(X_j) - h(X_j, \bar{q}_j) - d_j X_j + d_i X_i \tag{4.7}$$

Open Access

The definition of open access is that there is no management scheme. This implies that fishing vessels are free to move between any of the patches and can exploit the fishery until it is no longer profitable. This means fishing vessels view both patches as single large patch, moving between patches until profit levels at each patch are driven to zero for a marginal fisherman. This implies that the marginal fisher is the same for both patches. For the given market conditions p and c, the marginal fisher under open access can be used to find the OA steady state equilibrium stock levels.

$$p\bar{q}^{OA} X_i e - ce = 0$$

$$X^{OA} = \frac{c}{p\bar{q}^{OA}}$$

X^{OA} can then be substituted into the growth function to find OA steady state harvest level where $\dot{X} = 0$. Equations 4.8 to equation 4.11 form a set of simultaneous equations that solve for q^{OA} and X^{OA}.

$$p\bar{q}_i X_i e - ce = 0 \tag{4.8}$$

$$p\bar{q}_j X_j e - ce = 0 \tag{4.9}$$

$$\dot{X}_i = g(X_i) - h(X_i, \bar{q}) - d_i X_i + d_j X_j = 0 \tag{4.10}$$

$$\dot{X}_j = g(X_j) - h(X_j, \bar{q}) - d_j X_j + d_i X_i = 0 \tag{4.11}$$

In a single patch case, the profit function for the marginal fisher and the equation of motion for stocks are required to be solved simultaneously to determine open access effort and stock levels. For a multi-patch case, an additional concern is how fishing vessels will distribute themselves over the two countries. To determine the distribution of fishing vessels in each patch, first consider the decision that each fishing vessel has to make in each period under open access. Fishing vessel k has to choose between country i and country j. If profit levels are equal, it implies that stock levels must be equal as follows.

$$\pi_i = \pi_j$$

$$pq_k X_i e - ce = pq_k X_j e - ce$$

$$X_i = X_j$$

This condition means that fishing vessels will prefer to fish in the country with higher stock under open access. If the two stock levels and growth functions are identical, then all fishing vessels are indifferent between each patch and the fleet will be distributed equally between the two countries. Figure 4.1 shows the profit functions for two countries A and B, during the transition towards OA equilibrium. Only fishing vessels with $q \geq \bar{q}$ can afford to participate given the constraints imposed by market price of tuna p, cost of fishing c, and the maximum days of fishing in a season e_{max}.

To understand the transition dynamics under open access, consider a fisherman with $q_k = q_{OA}$. In the leftmost diagram in Figure 4.1, fishing vessel k would prefer to fish in country i given the higher profit levels. This is true for all other fishing vessels, and so country i stock gets depleted first until the profit levels are equal as shown in the middle diagram in Figure 4.1. The corresponding stock and harvest levels are shown in Figure 4.2 for two patches where $X_i > X_j$. Harvest in country i occurs until the stock level is equal to the stock level in country j, as shown in the left to middle diagram. During this transition, some fishing vessels who are not productive enough are forced to leave the fishery. Fisherman k, like all other fishermen who are still able to participate, is now indifferent between either patch as profit levels are equal. When this occurs, both patches get harvested at an equal rate until only fisherman with $q = q_k$ are left. This is the steady state open access level for both countries at X_{OA}. At this stock level, economic rent is equal to zero and all other fishing vessels have been forced to leave the fishery. This is shown in the rightmost diagram in Figure 4.1 and 4.2.

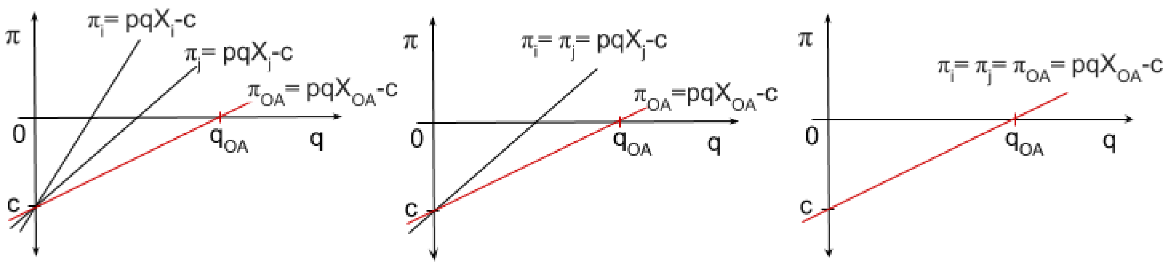


Figure 4.1: From left to right, profit functions for transition from unequal stock levels to open access equilibrium.

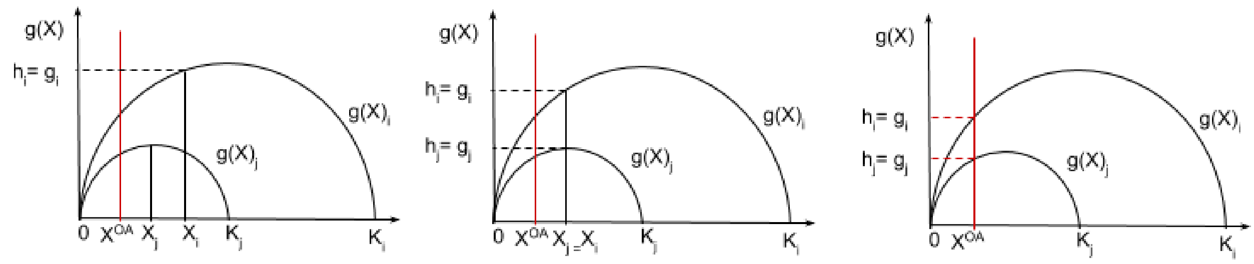


Figure 4.2: Stock, growth and harvest levels for transition from unequal stock levels to open access equilibrium, from left to right.

Fishing vessels are distributed over the two countries according to the relative size of the harvest levels from each country. Let $h_i^{OA}(X,q) = \beta h_j^{OA}(X,q)$ such that β represents the relative size between harvests. Then country i will receive

$$N_i = N(\frac{\beta}{1+\beta})$$

of the fishing vessels, and country j will receive

$$N_j = N(\frac{1}{1+\beta})$$

of the fishing vessels. For example, if harvest at OA equilibrium for country i is twice as large as country j, then country i will get two-thirds of the fleet, and country j will get one-third of the fleet.

Optimal Extraction

The optimal extraction solution maximizes total rent from the fishery over time. There are two possible approaches to finding an optimal solution, the full overlap approach or full separation approach. The harvest function for a full overlap approach has a single value $\bar{q}$ for both country i and j, as follows.

$$h = \int_{\bar{q}}^{q_{max}} q(X_i N_i + X_j N_j) e f(q) dq \tag{4.12}$$

For full separation, the harvest function requires separate $\bar{q}_i$ and $\bar{q}_j$ for each country. In addition this requires the manager to first maximize for country i from a to b to find $\bar{q}_i$, then maximize over the fishing vessels that are left from $\bar{q}_i$ to a. Essentially this process prioritizes one country over the other. The harvest function that will achieve this is

$$h = N \int_{\bar{q}_i}^{q_{max}} q X_i e f(q) dq + N \int_{\bar{q}_j}^{\bar{q}_i} q X_j e f(q) dq \tag{4.13}$$

This approach assumes that fishing vessels will sort efficiently between the two countries, with the most productive vessels fishing moving to the more productive patch. This may not be necessarily true, and this problem is examined in the next section. However, this assumption will be sufficient to characterize an optimal solution under full separation to compare to the full overlap case. The comparison will be based on the total rent from either approach.

The following are the general maximization problems for the fishery manager under full overlap and full separation. For full overlap, the number of fishing vessels in one of the patches is used as one of the control variables along with $\bar{q}$, in order to determine the effort to be expended in each fishery. Since $N = N_i + N_j$, this will determine the effort in the other patch as well. This is required because using only $\bar{q}$ would be equivalent to double counting the fleet size from $b - \bar{q}$. For full separation this is not required because there are two control variables in $\bar{q}_i$ and $\bar{q}_j$.

Full Overlap

For full overlap, the fishery manager maximizes the effort level expended by a single fishing fleet over both patches according to

$$\max_{\bar{q},N_i} \int_{-\infty}^{\infty} e^{-\rho t}[ph(X_i,\bar{q}) - cE_i(\bar{q}) + ph(X_j,\bar{q}) - cE_j(\bar{q})]dt$$

Subject to:

$$\dot{X}_i = g(X_i) - h(X_i,\bar{q}) - d_iX_i + d_jX_j \tag{4.14}$$

$$\dot{X}_j = g(X_j) - h(X_j,\bar{q}) - d_jX_j + d_iX_i \tag{4.15}$$

The current value Hamiltonian for setting a single price is

$$\begin{aligned} H = ph(X_i,\bar{q}) - cE_i(\bar{q}) + ph(X_j,\bar{q}_j) - cE_j(\bar{q}) + \lambda[g(X_i) - h(X_i,\bar{q}) - d_iX_i + d_jX_j] \\ + \mu[g(X_j) - h(X_j,\bar{q}) - d_jX_j + d_iX_i] \end{aligned}$$

Applying the maximum principle the following conditions are derived

$$\begin{aligned} \frac{\partial H}{\partial \bar{q}} &= ph_{\bar{q}}(X_i,\bar{q}) - cE_{\bar{q}} + \lambda h_{\bar{q}}(X_i,\bar{q}) = 0 \\ \frac{\partial H}{\partial N_i} &= ph_{N_i}(X_i,\bar{q}) - cE_{N_i} + \lambda h_{N_i}(X_i,\bar{q}) + ph_{N_j}(X_j,\bar{q}) - cE_{N_i} + \mu h_{N_i}(X_j,\bar{q}) = 0 \end{aligned} \tag{4.16}$$

$$\begin{aligned} \dot{\lambda} &= \lambda\rho - ph_x(X_i,\bar{q}) - \lambda(g_x(X_i) + h_x(X_i,\bar{q}) - d_i) - \mu d_i \\ \dot{\mu} &= \mu\rho - ph_x(X_j,\bar{q}) - \mu(g_x(X_j) + h_x(X_j,\bar{q}) - d_j) - \lambda d_j \end{aligned} \tag{4.17}$$

$$\begin{aligned} \dot{X}_i &= g(X_i) - h(X_i,\bar{q}) - d_iX_i + d_jX_j \\ \dot{X}_j &= g(X_j) - h(X_j,\bar{q}) - d_jX_j + d_iX_i \end{aligned} \tag{4.18}$$

For tractability in characterizing the equilibrium conditions I consider that there are no flows of stock between the patches, $d_iX_i = d_jX_j = 0$. At equilibrium, $\dot{X}_i = \dot{X}_j = 0$. which implies $\dot{\lambda} = \dot{\mu} = 0$. The conditions above reduce to

$$\Big(p - \frac{cE_{\bar{q}}}{h_{\bar{q}}}\Big)\rho = \Big(p - \frac{cE_{\bar{q}}}{h_{\bar{q}}}\Big)g_{x_i} + \frac{cE_{\bar{q}}}{X_ih_{\bar{q}}}g(X_i) \tag{4.19}$$

$$\Big(p - \frac{cE_{\bar{q}}}{h_{\bar{q}}}\Big)\rho = \Big(p - \frac{cE_{\bar{q}}}{h_{\bar{q}}}\Big)g_{x_j} + \frac{cE_{\bar{q}}}{X_jh_{\bar{q}}}g(X_j) \tag{4.20}$$

The solutions for X_i^*, X_j^*, $\bar{q}_i$ and $\bar{q}_j$ are derived simultaneously from 4.19,4.20 and the two equations of motion for stocks in 4.18.

Full Separation
For full separation, the fishery manager maximizes the effort level expended by a single fishing fleet over both patches according to

$$\max_{\bar{q}_i,\bar{q}_j} \int_{-\infty}^{\infty} e^{-\rho t}[ph(X_i,\bar{q}_i) - cE_i(\bar{q}_i) + ph(X_j,\bar{q}_j) - cE_j(\bar{q}_j)]dt$$

Subject to:

$$\dot{X}_i = g(X_i) - h(X_i,\bar{q}_i) - d_iX_i + d_jX_j \tag{4.21}$$

$$\dot{X}_j = g(X_j) - h(X_j,\bar{q}_j) - d_jX_j + d_iX_i \tag{4.22}$$

The current value Hamiltonian for the problem is

$$\begin{aligned} H = ph(X_i,\bar{q}_i) - cE_i(\bar{q}_i) + ph(X_j,\bar{q}_j) - cE_j(\bar{q}_j) + \lambda[g(X_i) - h(X_i,\bar{q}_i) - d_iX_i + d_jX_j] \\ + \mu[g(X_j) - h(X_j,\bar{q}_j) - d_jX_j + d_iX_i] \end{aligned}$$

Applying the maximum principle the following conditions are derived

$$\begin{aligned} \frac{\partial H}{\partial \bar{q}_i} &= (ph_{\bar{q}}(X_i,\bar{q}_i) - cE_{\bar{q}_i} - \lambda h_{\bar{q}}(X_i,\bar{q}_i) = 0 \\ \frac{\partial H}{\partial \bar{q}_j} &= (ph_{\bar{q}}(X_j,\bar{q}_j) - cE_{\bar{q}_j} - \lambda h_{\bar{q}}(X_j,\bar{q}_j) = 0 \end{aligned} \tag{4.23}$$

$$\begin{aligned} \dot{\lambda} &= \lambda\rho - ph_x(X_i,\bar{q}_i) - \lambda(g_x(X_i) + h_x(X_i,\bar{q}_i) - d_i) - \mu d_i \\ \dot{\mu} &= \mu\rho - ph_x(X_j,\bar{q}_j) - \mu(g_x(X_j) + h_x(X_j,\bar{q}_j) - d_j) - \lambda d_j \end{aligned} \tag{4.24}$$

$$\begin{aligned} \dot{X}_i &= g(X_i) - h(X_i,\bar{q}_i) - d_iX_i + d_jX_j \\ \dot{X}_j &= g(X_j) - h(X_j,\bar{q}_j) - d_jX_j + d_iX_i \end{aligned} \tag{4.25}$$

For tractability in characterizing the equilibrium conditions I consider that there are no flows of stock between the patches, $d_iX_i = d_jX_j = 0$. At equilibrium, $\dot{X}_i = \dot{X}_j = 0$. which implies $\dot{\lambda}_t = \dot{\mu}_t = 0$. The conditions above reduce to

$$\left(p - \frac{cE_{\bar{q}_i}}{h_{\bar{q}_i}}\right)\rho = \left(p - \frac{cE_{\bar{q}_i}}{h_{\bar{q}_i}}\right)g_{x_i} + \frac{cE_{\bar{q}_i}}{X_ih_{\bar{q}_i}}g(X_i) \tag{4.26}$$

$$\left(p - \frac{cE_{\bar{q}_j}}{h_{\bar{q}_j}}\right)\rho = \left(p - \frac{cE_{\bar{q}_j}}{h_{\bar{q}_j}}\right)g_{x_j} + \frac{cE_{\bar{q}_j}}{X_jh_{\bar{q}_j}}g(X_j) \tag{4.27}$$

The solutions for X_i^*, X_j^*, $\bar{q}_i$ and $\bar{q}_j$ are derived simultaneously from 4.26,4.27 and the two equations of motion for stocks in 4.25.

4.2.2 Steady State Characteristics

The main goal in this section is to determine how fishing vessels order themselves over the two countries in equilibrium. This will determine if optimal harvesting under input or output regulation can be supported at equilibrium. However, before considering supportability, general conditions for an equilibrium to be reached must be considered.

Proposition 3. *For any equilibrium to be reached, two conditions must be met. The first condition is that all fishing license markets should clear. The second condition is that fishing vessels maximize their profits.*

These are the two general conditions that can be used to assess whether an equilibrium has been reached, regardless of whether that equilibrium is considered desirable or not. Different equilibrium can be reached depending on the management scheme and price setting mechanism.

Proposition 4. *For any equilibrium under input and output regulation to be considered supportable, three conditions must be met. The first condition is that all fishing license markets should clear. The second condition is that fishing vessels maximize their profits. The third condition is the efficient ordering of fishing vessels over the two countries.*

For supportability of any equilibrium under input and output regulation, the same two general conditions for equilibrium are the minimal requirement. For full supportability a third condition is required, which is that at equilibrium fishing vessels efficiently order themselves over the two countries. This means that the most productive fishing vessels fish in most productive country, and the least productive vessels fish in the less productive country. Knowing which country each fishing vessel is operating in is important as it enables the manager to calculate the exact harvest level in each country. Any equilibrium that achieves the third condition will be more desirable than an equilibrium that does not because the manager will be sure that the target harvest levels will be reached.

The first condition is not difficult to achieve considering that equilibrium harvest levels are optimized to the size of the fleet. This implies that there are enough licenses for fishing vessels to buy, as long as they can all afford to do so. The second condition is also easy to achieve as it is an assumption that fishing vessels are profit maximizing and will buy licenses from the country that is the most profitable. The third condition is related to the profit maximizing condition of fishing vessels, but is a stronger condition that is not easy to achieve because it is imposed from the perspective of the manager. For this condition to be achieved, the incentives of each fishing vessels have to be aligned with the harvest function used which is unlikely to be the case.

For the following analysis, I will consider that all three conditions need to be met for an efficient outcome. However since the second condition is always assumed to be true, I focus on the market clearing and the efficient ordering condition. To check these conditions, I examine the fishing vessels problem both under input control and output control.

An implication of the linear profit function I have assumed, is that all fishing vessels will demand the highest possible number of license under either management scheme. In the case of input control, licenses are sold in per day effort units. The maximum number of licenses each fishing vessel can buy is equal to the total number of days in the season, and is the same over all fishing vessels. The license price under input control w_E, is equal to the marginal profit from each patch for the marginal fisher.

$$w_E = p\bar{q}X - c \tag{4.28}$$

In the case of output control, licenses are sold in harvest units. The maximum number of licenses a fishing vessel demands in a season is equal to the maximum possible seasonal catch tonnage, which depends on each fishing vessels productivity level q. The license price under input control w_H, is equal to the marginal profit for the marginal fisher.

$$w_H = p - \frac{c}{\bar{q}X} \tag{4.29}$$

In order to correctly characterize the individual vessel level incentives, first I have to determine if the stock levels X for each country will be the same in equilibrium for full overlap and full separation. This can be determined by examining the total harvest function for the fleet. From 4.12 for full overlap, harvest is a function of $\bar{q}$ and also N. This implies that although there may be a single $\bar{q}$, there can be two separate harvest levels for each patch, because the number of fishing vessels operating in each patch can be adjusted. From 4.13, although there is only a single N, there are two separate $\bar{q}$ and so there can be separate harvest levels for each patch. This implies that steady state stock levels can indeed be different over each patch. This is demonstrated in Figure 4.3, which illustrates harvest functions plot alongside the stock growth functions for each patch.

It is important to note that harvest is increasing in the stock level X. This is a consistent with 4.12 and 4.13, regardless of whether the harvest function is linear or not. As Figure 4.3 (a) shows, even with a single harvest function there will be two separate stock levels for each patch. Figure 4.3 (b) shows the case when there are separate harvest functions for each patch. Once again there are two separate stock levels. This has important implications for the ordering of the fishing vessels because it affects the profit functions of individual fishing vessels. Different steady state stock levels implies that there will be separate prices for licenses from each patch under full overlap and full separation, given 4.28 and 4.29. The only exception is when both stock and $\bar{q}$ levels are equal, which occurs under full overlap with identical countries.

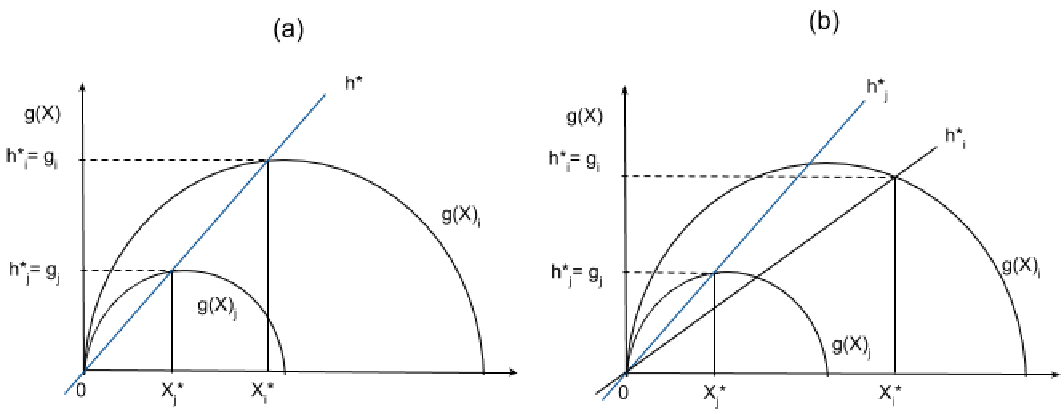


Figure 4.3: Harvest levels at equilibrium under optimal management for two countries, i and j. (a) shows the harvest levels with a single harvest function; and (b) shows the two separate harvest functions.

The relationship between harvest and $\bar{q}$ is that the value of $\bar{q}$ decreases as the equilibrium harvest h^* increases. The intuition behind this is that a larger harvest size requires more fishing vessels, which means the marginal fisher must have a lower q to increase $(b - \bar{q})$. In the case where the manager maximizes for each country over the entire fleet, for country i with a more productive fishery than j, $h^{*i} > h^{*j}$ and $\bar{q}^i < \bar{q}^j$.

$$h^{*i} = \int_{\bar{q}^i}^{b} qX_i ef(q)dq > \int_{\bar{q}^j}^{b} qX_j ef(q)dq = h^{*j}$$

When choosing a patch to fish in, each fishing vessel has to consider the relative profitability between each patch. This is the trade-off between the increase in revenue from the patch with the larger stock, versus the increase in the license price to fish in the higher stock patch. If $X_i > X_j$, all other things equal it means that $w_i > w_j$ also. To compare relative profitability, I introduce the idea of a transition value $\hat{q}$, which is the value of q where profit in each patch is equalized. A fishing vessel with a $q = \hat{q}$ is indifferent between fishing in either country. A fishing vessel with a $q > \hat{q}$ will prefer to fish in country i, and a fishing vessel with a $q < \hat{q}$ will prefer to fish in country j.

For each management scheme I consider the profit functions of fishing vessels for full overlap and full separation.

Input Regulation

The profit function for a fishing vessel under input regulation is

$$\pi_E = p\bar{q}Xe - w_E e - ce$$

These are shown in Figure 4.4 (a) for full overlap with a single $\bar{q}$, and Figure 4.4 (b) for full separation, where $\bar{q}_A$, $\bar{q}_B$, and $\hat{q}$ are also shown. The expression for $\hat{q}$ is found by setting the profit levels equal to each other.

$$\hat{q} = \frac{\bar{q}_i X_i - \bar{q}_j X_j}{X_i - X_j} \tag{4.30}$$

For fishing vessel k to prefer to fish in country i, its catchability value q_k must meet two criteria. The first is based on the profit function between the two countries

$$q_k > \hat{q}$$

The second second condition is that vessel k must be productive enough to afford a license from country i.

$$q_k \geq \bar{q}_i$$

Similarly, for fishing vessel k to prefer to fish in country j, the corresponding conditions that must be met are

$$q_k < \hat{q}$$

$$q_k \geq \bar{q}_j$$

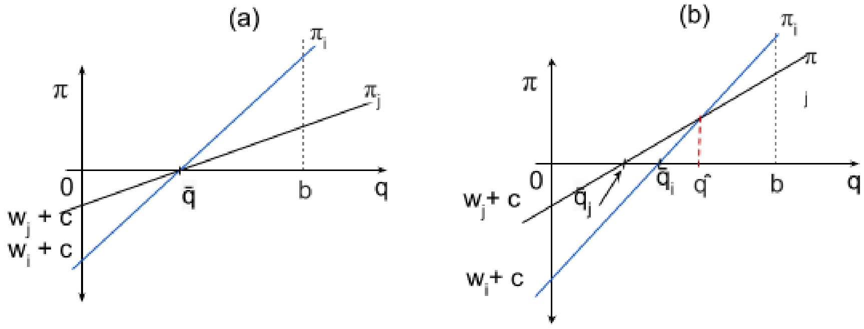


Figure 4.4: Equilibrium under input regulation for two countries, i and j where i is the larger country. (a) shows the profit functions under full overlap; and (b) shows the profit functions from full separation.

Proposition 5. *Under the assumption of competition and heterogeneous fishers, input regulation under full overlap can achieve the market clearing condition. The efficient ordering condition is also possible, but is unlikely to be achieved.*

Proof. As long as there is a single $\bar{q}$, if $\pi_i > \pi_j$ all fishing vessels prefer to fish in country i. Once all the licenses in country i have been sold, fishing vessels will have no choice but to buy from country j, and the market will clear. This is because it is still profitable to fish in country j.

Efficient ordering is also possible, but not likely. If the most productive fishing vessels were to buy licenses first, then the less productive fishing vessels would have no choice but to buy from country j. If at least one fishing vessels with lower $\bar{q}$ may be able to purchase licenses in the more productive patch, then a more productive fishing vessel would be pushed out and forced to buy licenses in country j. It is easy to see that efficient ordering can only be achieved under very specific conditions. □

Proposition 6. *Under the assumption of competition and heterogeneous fishers, input regulation under full separation can achieve both market clearing and efficient ordering conditions under very specific conditions.*

Proof. First consider if $X_i = X_j$. Since $\bar{q}_i > \bar{q}_j$ is a condition specified in the harvest equation, this must mean that $w_i > w_j$ and $\pi_i < \pi_j$ for all values of q. Since $X_i = X_j$ and $\bar{q}_i > \bar{q}_j$, the profit function lines will be parallel to each other, but the profit function for country j will be above country i. This situation implies that fishing vessels prefer to fish in country j because higher license prices in country i have made it less profitable. If the less productive fishing vessels were to buy the licenses first, they would exhaust the licenses from j and the more productive vessels will be forced to buy from country i. The market would clear, and efficient ordering will be achieved. However, if all fishing vessels are allowed to buy the licenses simultaneously, then all it takes is a single higher productivity vessel with $q > \bar{q}_i$ to fish in country j, to force a less productive fishing vessel with $q < \bar{q}_i$ out of the fishery because it cannot afford to buy from country i. In this case the market will not clear.

Now consider if $X_i > X_j$. Again $\bar{q}_i > \bar{q}_j$ which means $w_i > w_j$ and $\pi_i < \pi_j$. Since $X_i > X_j$, the profit function for country i is steeper. This implies at very high productivity levels they will meet and country i will be more profitable . As the difference in X_i and X_j increases, the profit function for country i grows steeper until it looks like something resembling Figure 4.4 (b). The intersection point will be the value $\hat{q}$. In this case all fishing vessels with $q_i > \hat{q}$ will prefer to fish in country i, and all vessels with $q_j < \hat{q}$ will prefer to fish in country j, subject to $b > \hat{q}$. In this case, efficient ordering is guaranteed without any conditions on the sale of the licenses imposed by the manager.

□

Output Regulation

The profit function for a fishing vessel under output regulation is

$$\pi_H = p\bar{q}Xe - w_H\bar{q}Xe - ce$$

This is shown in Figure 4.4 for both full overlap and for full separation. The profit functions are the same in either case because all fishing vessels will have the same relative profitability regardless of productivity levels. This can be seen by looking at the expression for $\hat{q}$ under output regulation. This result implies that price levels do not matter, and that the patch with the higher stock will yield higher profit levels.

$$\begin{aligned}
p\hat{q}X_ie - w_i\hat{q}X_ie - ce &= p\hat{q}X_je - w_j\hat{q}X_je - ce \\
p\hat{q}X_i - (p - \frac{c}{\bar{q}_iX_i})\hat{q}X_i &= p\hat{q}X_j - (p - \frac{c}{\bar{q}_jX_j})\hat{q}X_j \\
p\hat{q}X_i - p\hat{q}X_i + \frac{c\hat{q}}{\bar{q}_i} &= p\hat{q}X_j - p\hat{q}X_j + \frac{c\hat{q}}{\bar{q}_j} \\
\frac{\hat{q}}{\bar{q}_i} &= \frac{\hat{q}}{\bar{q}_j} \\
\bar{q}_j &= \bar{q}_i
\end{aligned} \tag{4.31}$$

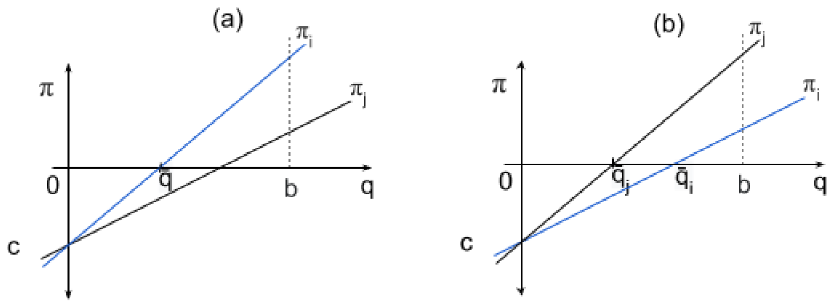


Figure 4.5: Equilibrium under output regulation for two countries, i and j. Figure (a) shows the profit function from full overlap, resulting in a single $\bar{q}$; (b) shows the profit functions from optimizing over each country separately, resulting in $\bar{q}_i$ and $\bar{q}_j$.

Proposition 7. *Under the assumption of competition and heterogeneous fishers, output regulation under full overlap may be able to clear the license market, but it will not achieve an efficient ordering unless the two patches are identical.*

Proof. Under full overlap there is only one $\bar{q}$. However since there are different stock levels at steady state, one patch will always be more profitable than the other. Let country i be the country with the higher stock level, and country j the lower stock level. No fishing vessel will prefer to fish in country j, and so this implies that all fishing vessels will buy from country i first. When the licenses for country i run out, then fishing vessels will buy from country j. Under this scenario if the lower productivity vessels are able to buy licenses first, it is possible that the market can clear. This is because only fishing vessels with higher profitability can afford to buy from country j, since $\bar{q}_i < \bar{q}_j$. If there are no conditions imposed on buying of licenses, then the license market will not clear because the more productive fishing vessels will buy from country i, pushing out lower productive fishing vessels, who will not be able to afford licenses from country j. This also means that it is impossible for efficient ordering to be achieved. □

Proposition 8. *Under the assumption of competition and heterogeneous fishers, output regulation under full separation may be able to clear the license market, which means it is also possible that efficient ordering can be achieved. However, this is unlikely to occur.*

Proof. Let country i be the country with the higher stock level, and country j the lower stock level. Under full separation there are individual cutoff levels $\bar{q}_i$ and $\bar{q}_j$. In addition, the harvest function imposes the condition that $\bar{q}_i > \bar{q}_j$. Since there are different stock levels at steady state, depending on the license prices one patch may be more profitable than the other or they could be equally profitable. Consider that if the price of licenses for country i is set high enough, country j may be more profitable than country i. This implies that all fishing vessels will buy from the country j first. When the licenses for country j run out, then fishing vessels will buy from country i. Under this scenario the market can clear only if the less productive fishing vessels buy their licenses first, in which case efficient ordering can be achieved. This is because less productive fishing vessels will fish in country j and the the most efficient fishing vessels can only buy licenses to fish in country i. However, it only takes one high productivity fishing vessel to buy licenses first, pushing out the lower productivity vessel out of the fishery. □

The implication of condition 4.31 is that under the assumptions made in this study, output regulation is not likely to achieve the market clearing condition. In addition, output regulation under full separation will not be able to achieve efficient ordering. These results may appear a little extreme, and may not necessarily reflect what is observed in the real world. One of the reasons for the result is the constant cost assumption for c. In Figure 4.6, I show that it is possible for fishing vessels to distribute as in the effort case for different license prices if the costs of fishing in each patch are different. For example, if one patch is further away or the weather or fishing conditions are not as favorable as another patch.

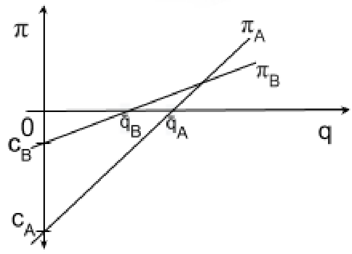


Figure 4.6: This figure shows that if the constant cost assumption is relaxed, it is possible to have an efficient ordering with separate license prices.

4.3 Application

The purpose of this section is to illustrate the heterogenous model using parameter estimates baased loosely on the PNA fishery for skipjack tuna. The full overlap and full separation cases are also compared by examining total rent. First the functional forms characterizing the model are outlined. Then I show results from simulations for the model using parameter estimates.

4.3.1 Model

Under the assumption that $f(q)$ is a uniform probability density function with $q_{max} = b$ and $q_{min} = a$, the full overlap harvest equation from 4.12 is

$$h = \int_{\bar{q}}^{b} q(X_i + X_j)e\Big(\frac{N}{b-a}\Big)dq = \Big[\frac{q^2}{2(b-a)}X_i eN\Big]_{\bar{q}}^{b}$$

$$h(X,\bar{q}) = (b^2 - \bar{q}^2)\frac{(X_i + X_j)eN}{2(b-a)} \tag{4.32}$$

Total actual effort is

$$\bar{E}_i = eN_i \int_{\bar{q}}^{b} f(q)dq = \frac{(b-\bar{q})eN_i}{b-a} \tag{4.33}$$

$$\bar{E}_j = eN_j \int_{\bar{q}}^{b} f(q)dq = \frac{(b-\bar{q})eN_j}{b-a} \tag{4.34}$$

For full separation, the harvest equation that reflects efficient sorting of fishing vessels from 4.13 is

$$h = \int_{\hat{q}}^{b} qX_i e\Big(\frac{N}{b-a}\Big)dq + \int_{\bar{q}_j}^{\hat{q}} qX_j e\Big(\frac{N}{b-a}\Big)dq = \Big[\frac{q^2}{2(b-a)}X_i eN\Big]_{\hat{q}}^{b} + \Big[\frac{q^2}{2(b-a)}XeN\Big]_{\bar{q}_j}^{\hat{q}}$$

$$h(X,\bar{q}) = (b^2 - \hat{q}^2)\frac{X_i eN}{2(b-a)} + (\hat{q}^2 - \bar{q}_j{}^2)\frac{X_j eN}{2(b-a)} \tag{4.35}$$

Total actual effort is

$$\bar{E}_i = eN_i \int_{\hat{q}}^{b} f(q)dq = \frac{(b-\hat{q})eN_i}{b-a} \tag{4.36}$$

$$\bar{E}_j = eN_j \int_{\bar{q}_j}^{\hat{q}} f(q)dq = \frac{(\hat{q} - \bar{q}_j)eN_j}{b-a} \tag{4.37}$$

The functional forms of the equations of motion, which are the same for full overlap and full separation, are as follows.

$$\dot{X}_i = r_i X_i - \frac{r_i X_i^2}{K_i} - X_i eN \frac{(b^2 - \hat{q}^2)}{2(b-a)} - d_i X_i + d_j X_j = 0 \tag{4.38}$$

$$\dot{X}_j = r_i X_i - \frac{r_j X_j^2}{K_j} - X_j eN \frac{(\hat{q}^2 - \bar{q}_j{}^2)}{2(\hat{q}-a)} - d_j X_j + d_i X_j = 0 \tag{4.39}$$

Open Access

Under the assumption that $K_i > \frac{c}{pq_i}$ and $K_j > \frac{c}{pq_j}$, the steady state stock size for the two patches under open access are

$$p\bar{q}^{OA} X_i e - ce = 0$$
$$p\bar{q}^{OA} X_j e - ce = 0$$

This yields open access stock levels

$$X_i^{OA} = \frac{c}{p\bar{q}^{OA}}$$
$$X_j^{OA} = \frac{c}{p\bar{q}^{OA}}$$

To find $\bar{q}_i^{OA}$ and $\bar{q}_j^{OA}$, substitute X_i^{OA} and X_j^{OA} into the equation of motion for stocks (4.38) and (4.39), which both equal to zero at steady state. This implies $g(X) = h(\bar{q}, X)$. Disregarding flows between patches, this becomes

$$r_i - \left[\frac{c}{p\bar{q}^{OA}}\right]\frac{r_i}{K_i} = eN_i \frac{(b^2 - \bar{q}^{OA^2})}{2(b-a)}$$
$$r_i - \left[\frac{c}{p\bar{q}^{OA}}\right]\frac{r_j}{K_j} = eN_j \frac{(b^2 - \bar{q}^{OA^2})}{2(b-a)}$$

This means that N_i and N_j can be identified, which then identifies effort levels in each patch in open access equilibrium.

Optimal Extraction

If both patches were under single ownership, the owner would maximize the effort level expended over both patches according to

$$\max_{\hat{q},\bar{q}_j} \int_a^b e^{-\rho t}[ph(X_{i,t}, \hat{q}) - cE_{i,t}(\hat{q}) + ph(X_{j,t}, \bar{q}_j) - cE_{j,t}(\bar{q}_j)]dt$$

Subject to:

$$\dot{X}_i = g(X_i) - h(X_i, \hat{q}) - d_i X_i + d_j X_j \tag{4.40}$$
$$\dot{X}_j = g(X_j) - h(X_j, \bar{q}_j) - d_j X_j + d_i X_i \tag{4.41}$$

Full Overlap
The current value Hamiltonian for setting a single price is

$$H = ph(X_i, \bar{q}) - cE_i(\bar{q}) + ph(X_j, \bar{q_j}) - cE_j(\bar{q}) + \lambda[g(X_i) - h(X_i, \bar{q}) - d_iX_i + d_jX_j] \\ + \mu[g(X_j) - h(X_j, \bar{q}) - d_jX_j + d_iX_i]$$

Since there is only a single $\bar{q}$ to be determined, the second control variable will have to be N_i. This is the only way that the proportion of fishing vessels operating in either patch can be determined. To make this work, set $N_j = N - N_i$ in the maximization problem. Applying the maximum principle the following conditions are derived

$$\begin{aligned} \frac{\partial H}{\partial \bar{q}} &= ph_{\bar{q}}(X_i, \bar{q}) - cE_{\bar{q}} + \lambda h_{\bar{q}}(X_i, \bar{q}) = 0 \\ \frac{\partial H}{\partial N_i} &= ph_{N_i}(X_i, \bar{q}) - cE_{N_i} + \lambda h_{N_i}(X_i, \bar{q}) + ph_{N_j}(X_j, \bar{q}) - cE_{N_i} + \mu h_{N_i}(X_j, \bar{q}) = 0 \end{aligned} \tag{4.42}$$

$$\begin{aligned} \dot{\lambda} &= \lambda\rho - ph_x(X_i, \bar{q}) - \lambda(g_x(X_i) + h_x(X_i, \bar{q}) - d_i) - \mu d_i \\ \dot{\mu} &= \mu\rho - ph_x(X_j, \bar{q}) - \mu(g_x(X_j) + h_x(X_j, \bar{q}) - d_j) - \lambda d_j \end{aligned} \tag{4.43}$$

$$\begin{aligned} \dot{X}_i &= g(X_i) - h(X_i, \bar{q}) - d_iX_i + d_jX_j \\ \dot{X}_j &= g(X_j) - h(X_j, \bar{q}) - d_jX_j + d_iX_i \end{aligned} \tag{4.44}$$

For tractability, from this point forward in characterizing the conditions I consider that there is no flows of stock between the patches, $d_iX_i = d_jX_j = 0$. At equilibrium, $\dot{X}_i = \dot{X}_j = 0$. which implies $\dot{\lambda} = \dot{\mu} = 0$. The conditions above reduce to

$$\Big(p - \frac{cE_{\bar{q}}}{h_{\bar{q}}}\Big)\rho = \Big(p - \frac{cE_{\bar{q}}}{h_{\bar{q}}}\Big)g_{x_i} + \frac{cE_{\bar{q}}}{X_ih_{\bar{q}}}g(X_i)$$

$$\Big(p - \frac{cE_{\bar{q}}}{h_{\bar{q}}}\Big)\rho = \Big(p - \frac{cE_{\bar{q}}}{h_{\bar{q}}}\Big)g_{x_j} + \frac{cE_{\bar{q}}}{X_jh_{\bar{q}}}g(X_j)$$

(For derivations refer to Appendix 4.B) The shadow prices are

$$\lambda = p - \frac{c}{\bar{q}X_i}$$

$$\mu = p - \frac{c}{\bar{q}X_j}$$

From the steady state conditions, substituting for $g(X)$ and $h(X, \bar{q})$ and rearranging gives me

$$X_i^2\frac{2pr_i}{K_i} + X_i\Big(p\rho - pr_i - \frac{cr_i}{K_i\bar{q}}\Big) + \frac{cr_i}{\bar{q}} = 0 \tag{4.45}$$

$$X_j^2\frac{2pr_j}{K_j} + X_j\Big(p\rho - pr_j - \frac{cr_j}{K_j\bar{q}}\Big) + \frac{cr_j}{\bar{q}} = 0 \tag{4.46}$$

The solution for X_i^* takes the following form.

$$X_i^* = \frac{-B_i \pm \sqrt{B_i^2 - 4A_iC_i}}{2A_i} \tag{4.47}$$

where

$$A_i = \frac{2pr_i}{K_i}; B_i = p\rho - pr_i - \frac{2cr_i}{K_i\bar{q}}; C_i = \frac{cr_i}{\bar{q}}$$

and

$$X_j^* = \frac{-B_j \pm \sqrt{B_j^2 - 4A_jC_j}}{2A_j} \tag{4.48}$$

where

$$A_j = \frac{2pr_j}{K_j}; B_j = p\rho - pr_j - \frac{2cr_j}{K_j\bar{q}}; C_j = \frac{cr_j}{\bar{q}}$$

Full Separation

The current value Hamiltonian for setting separate prices is

$$\begin{aligned} H = ph(X_i, \hat{q}) - cE_i(\hat{q}) + ph(X_j, \bar{q}_j) - cE_j(\bar{q}_j) + \lambda[g(X_i) - h(X_i, \hat{q}) - d_iX_i + d_jX_j] \\ + \mu[g(X_j) - h(X_j, \bar{q}_j) - d_jX_j + d_iX_i] \end{aligned}$$

Applying the maximum principle the following conditions are derived

$$\begin{aligned} \frac{\partial H}{\partial \hat{q}} &= (ph_{\bar{q}}(X_i, \hat{q}) - cE_{\hat{q}} - \lambda h_{\bar{q}}(X_i, \hat{q}) = 0 \\ \frac{\partial H}{\partial \bar{q}_j} &= (ph_{\bar{q}}(X_j, \bar{q}_j) - cE_{\bar{q}_j} - \lambda h_{\bar{q}}(X_j, \bar{q}_j) = 0 \end{aligned} \tag{4.49}$$

$$\begin{aligned} \dot{\lambda} &= \lambda\rho - ph_x(X_i, \hat{q}) - \lambda(g_x(X_i) + h_x(X_i, \hat{q}) - d_i) - \mu d_i \\ \dot{\mu} &= \mu\rho - ph_x(X_j, \bar{q}_j) - \mu(g_x(X_j) + h_x(X_j, \bar{q}_j) - d_j) - \lambda d_j \end{aligned} \tag{4.50}$$

$$\begin{aligned} \dot{X}_i &= g(X_i) - h(X_i, \hat{q}) - d_iX_i + d_jX_j \\ \dot{X}_j &= g(X_j) - h(X_j, \bar{q}_j) - d_jX_j + d_iX_i \end{aligned} \tag{4.51}$$

For tractability, from this point forward in characterizing the conditions I consider that there is not flows of stock between the patches, $d_iX_i = d_jX_j = 0$. At equilibrium, $\dot{X}_i = \dot{X}_j = 0$. which implies $\dot{\lambda} = \dot{\mu} = 0$. The conditions above reduce to

$$\Big(p - \frac{cE_{\hat{q}}}{h_{\hat{q}}}\Big)\rho = \Big(p - \frac{cE_{\hat{q}}}{h_{\hat{q}}}\Big)g_{x_i} + \frac{cE_{\hat{q}}}{X_ih_{\hat{q}}}g(X_i) \tag{4.52}$$

$$\Big(p - \frac{cE_{\bar{q}_j}}{h_{\bar{q}_j}}\Big)\rho = \Big(p - \frac{cE_{\bar{q}_j}}{h_{\bar{q}_j}}\Big)g_{x_j} + \frac{cE_{\bar{q}_j}}{X_jh_{\bar{q}_j}}g(X_j) \tag{4.53}$$

(For derivations refer to Appendix 4.C) The shadow prices are

$$\lambda = p - \frac{c}{\bar{q}_j X_i}$$

$$\mu = p - \frac{c}{\bar{q}_j X_j}$$

From equation 4.52 and 4.53, substituting for $g(X)$ and $h(X, \bar{q})$ and rearranging yields

$$X_i^2 \left[\frac{2pr_i}{K_i}\right] - X_i \left[p\rho - pr_i - \frac{cr_i}{\bar{q}_j K_i}\right] + \frac{c\rho}{\bar{q}_j} = 0 \tag{4.54}$$

$$X_j^2 \left[\frac{2pr_j}{K_j}\right] + X_j \left[p\rho - pr_j - \frac{cr_j}{\bar{q}_j K_j}\right] + \frac{c\rho}{\bar{q}_j} = 0 \tag{4.55}$$

The solution for X_i^* takes the following form, which can be positive or negative. The positive root is the solution in this case. For country i,

$$X_i^* = \frac{-B_i \pm \sqrt{B_i^2 - 4A_iC_i}}{2A_i}$$

where

$$A_i = \frac{2pr_i}{K_i}$$

$$B_i = p\rho - pr_i - \frac{cr_i}{\bar{q}_j K_i}$$

$$C_i = \frac{c\rho}{\bar{q}_j}$$

For country j,

$$X_j^* = \frac{-B_j \pm \sqrt{B_j^2 - 4A_jC_j}}{2A_j}$$

where

$$A_j = \frac{2pr_j}{K_j}$$

$$B_j = p\rho - pr_j - \frac{cr_j}{\bar{q}_j K_j}$$

$$C_j = \frac{c\rho}{\bar{q}_j}$$

Equations 4.54 and 4.55, along with the equations of motion for stock 4.40 and 4.41 form a set of four simultaneous equations which determine equilibrium stock levels (X_i^* and X_j^*) and cutoff catchability values ($\bar{q}_i$ and $\bar{q}_j$). Once these are found, the harvest levels, effort levels and the corresponding licenses can be determined.

4.3.2 Parameter Estimations

The justification for the initial parameters which I will consider the baseline parameters are outlined in Section 3.3. Total carrying capacity for the PNA is $K = 16,000,000$. For each country, this total carrying capacity will be split from equal to very unequal shares. Stock intrinsic growth rate $r = 0.36$ per year, $q = 0.0006$, $p = 2000$ per ton, $c = 2000000$ per vessel per year, and $\rho = 0.1$. $a = 0.0002$ and $b = 0.0009$. It should be noted that the values of a and b were chosen so as to ensure that $q = \bar{q}$.

4.3.3 Simulation Results

First I present simulation results for the homogeneous model, comparing revenue from input to output regulation. Then I present the results for the heterogeneous model comparing total rent to the fishery for full overlap and full separation. Finally I present the results for the heterogeneous model comparing revenue from input to output regulation.

Standard Model

Two simulations for the homogeneous case were run. The first simulation varied the value of q, while holding stock levels for Country i and Country j at 12 million and 4 millions tons respectively (Table 4.1). The second simulation varied the stock levels for each country from a large difference to a small difference (Table 4.2). The first two rows in Table 4.2 refers to a case single country case. As expected the main results for the standard model from Chapter 1 still hold, which is that an increase in q leads to a reduction in revenue. This is because increasing the value of q leads a reduction in the price of a license, which more than offsets the increase in the number of licenses. However, a new result specific to the two country case is that if the difference in stock levels between the two countries is large enough, it will not be feasible for the small country to sell all of its licenses. This can be seen in row 4 of Table 4.2, where the license price and revenue are negative. In actual application, the country may have a certain price level below which where it will not sell. This will result in a surplus of licenses for that country.

q	K	X	E	P/day	Rev Input	h	P/ton	Rev Output
0.00040	12,000,000	6,815,174	344.43	22,965	1,423,759	1,408,414	1,010.90	1,423,759
0.00040	4,000,000	3,622,342	464.16	7,001	584,894	1,008,812	579.78	584,894
0.00050	12,000,000	6,364,937	361.31	20,714	1,347,142	1,379,848	976.30	1,347,142
0.00050	4,000,000	3,235,641	478.66	5,067	436,578	929,270	469.81	436,578
0.00060	12,000,000	6,056,018	372.90	19,169	1,286,658	1,354,971	949.58	1,286,658
0.00060	4,000,000	2,971,083	488.58	3,744	329,294	870,975	378.07	329,294
0.00070	12,000,000	5,830,222	381.37	18,040	1,238,374	1,334,071	928.27	1,238,374
0.00070	4,000,000	2,777,778	495.83	2,778	247,917	826,389	300.00	247,917
0.00080	12,000,000	5,657,644	387.84	17,177	1,199,150	1,316,551	910.83	1,199,150
0.00080	4,000,000	2,629,860	501.38	2,038	183,943	791,136	232.51	183,943

Table 4.1: Homogeneous 2 country case - varying value of q from $0.0004 - 0.0008$, and keeping $K_i = 14$ million tons and $K_j = 2$ million tons. (Revenue in 000's)

q	K	X	E	P/day	Rev Input	h	P/ton	Rev Output
0.00060	16,000,000	7,543,526	317.12	26,607	1,518,732	1,435,312	1,058.12	1,518,732
0.00060	0	0	0	0	0	0	0	0
0.00060	14,000,000	6,801,926	344.93	22,899	1,421,700	1,407,704	1,009.94	1,421,700
0.00060	2,000,000	2,123,962	520.35	0	0	663,124	0	0
0.00060	12,000,000	6,056,018	372.90	19,169	1,286,658	1,354,971	949.58	1,286,658
0.00060	4,000,000	2,971,083	488.58	3,744	329,294	870,975	378.07	329,294
0.00060	10,000,000	5,304,114	401.10	15,409	1,112,520	1,276,474	871.56	1,112,520
0.00060	6,000,000	3,769,102	458.66	7,734	638,541	1,037,239	615.62	638,541
0.00060	8,000,000	4,543,450	429.62	11,606	897,522	1,171,176	766.34	897,522
0.00060	8,000,000	4,543,450	429.62	11,606	897,522	1,171,176	766.34	897,522

Table 4.2: Homogeneous 2 country case - varying value of K for each country, and keeping $q = 0.0006$. (Revenue in 000's)

Heterogeneous Model

Two sets of simulations were run comparing total rents from the fishery for two countries, i and j. Table 4.4 shows the results of the simulation for full overlap cases, and Table 4.3 shows the results of the simulations for full separation. In each table four different scenarios with varying stock carrying capacity K were simulated. The first scenario is where the carrying capacity for both countries is $K_i = K_j = 8$ million tons. The second is where $K_i = 10$ million tons, and $K_j = 6$ million tons. The third is where $K_i = 12$ million tons, and $K_j = 4$ million tons. Finally the fourth is where $K_i = 14$ million tons, and $K_j = 2$ million tons. The last case where $K_i = 14$ million tons, and $K_j = 2$ million tons is omitted.

Figures 4.7, 4.8 and 4.9 show the steady state equilibrium stock and harvest functions for the cases where $K_i = K_j = 8$ million tons, $K_i = 10$ million tons and $K_j = 6$ million tons, and $K_i = 12$ million tons and $K_j = 4$ million tons respectively. These figures correspond to the cases in the tables. The last case where $K_i = 14$ million tons, and $K_j = 2$ million tons is omitted. Similarly, Figures 4.11, 4.10, 4.13 and 4.12 show the profit levels for input regulation and output regulation under both full overlap and full separation case. In each of the fours cases I provide simulations that correspond to the three different country sizes, with the last case where $K_i = 14$ million tons, and $K_j = 2$ million tons being omitted.

The tables show the carrying capacity K in the first collumn, followed by the cutoff catchability rate $\bar{q}$, then equilibrium stock level X, harvest level h, and effort level E. N represents the number of fishing vessels operating in each fishery, which is required to determine the correct effort level under full overlap. In full separation, N is equal to the entire fleet size because effort is determined by the separate cutoff levels. Column 7 shows the total potential rent to the entire fishery, including the fishing vessels. Column 8 shows the price of a licenses under input regulation, and column 9 shows the profit level to each country for input regulation. The last two columns shows license price and profit levels to each country under output regulation.

The first result is that steady state stock levels and harvest levels are identical under full overlap and full separation. The optimal $\bar{q}$ value is the same for the smaller country under both cases, but effort levels are not. This means that while total rent over both

$K(000's)$	$\bar{q}$	X	h	E	N	Rent	w_E	π_E	w_H	π_H
14,000	0.00065	6,686,157	1,257,467	41,117	517	1,429,344	24,919	1,024,584	1,037	1,304,522
2,000	0.00065	2,034,680	0	0	0	0	0	0	0	0
12,000	0.00050	6,383,072	1,075,598	40,575	357	1,162,567	15,224	617,707	867	932,684
4,000	0.00050	3,251,186	219,108	16,227	143	148,357	2,303	37,364	257	56,417
10,000	0.00044	5,853,851	873,754	37,359	296	895,528	10,271	383,699	721	629,553
6,000	0.00044	4,279,956	441,703	25,831	204	375,543	4,522	116,802	434	191,642
8,000	0.00042	5,147,724	660,723	32,482	250	630,175	7,015	227,864	581	383,564
8,000	0.00042	5,147,724	660,723	32,482	250	630,175	7,015	227,864	581	383,564

Table 4.3: Heterogeneous full overlap - holding $a = 0.0002$ and $b = 0.001$ while varying K_i and K_j. (Revenue in 000's)

$K(000's)$	$\bar{q}$	X	h	E	N	Rent	w_E	π_E	w_H	π_H
14,000	0.00063	6,686,157	1,257,467	41,511	500	1,424,965	24,048	998,244	1,026	1,290,109
2,000	0.00065	2,034,680	0	0	0	0	0	0	0	0
12,000	0.00068	6,383,072	1,075,598	36,135	500	1,211,902	24,996	903,220	1,038	1,116,912
4,000	0.00050	3,251,186	219,108	20,668	500	99,022	2,303	47,588	257	56,417
10,000	0.00072	5,853,851	873,754	31,191	500	964,065	24,146	753,137	1,027	897,592
6,000	0.00044	4,279,956	441,703	31,999	500	307,007	4,522	144,693	434	191,642
8,000	0.00077	5,147,724	660,723	26,140	500	700,635	21,819	570,355	994	656,677
8,000	0.00042	5,147,724	660,723	38,823	500	559,715	7,015	272,349	581	383,564

Table 4.4: Heterogeneous full separation - holding $a = 0.0002$ and $b = 0.001$ while varying K_i and K_j. (Revenue in 000's)

countries are the same, the distribution of rent over the two countries between full overlap and full separation are not the same. The larger country receives a higher proportion of the rent under full separation relative to full overlap. If the full separation model is applied to two identical countries, the rent levels will not be the same. This is because one country requires additional effort days to fish an equivalent amount of fish than the other due to the less productive vessels that it has. This can be seen in the last two rows of Table 4.3. The second result is that if two countries are significantly different to each other in terms of size of fish stocks, an optimal solution where the small country can participate may not be feasible. This is demonstrated in the first two grayed out rows of both tables, and is the reason this case is omitted from the figures.

The last four columns of the tables show the revenue levels from licenses sales for both input regulation and output regulation under the best case scenario. That is, if prices were set at the corresponding $\bar{q}$ levels, and under the assumption that the market clearing and efficient ordering conditions are achieved. As the tables show, revenue under output regulation would yield higher returns from licenses sales. However, these result only hold if the both conditions for efficiency are achieved. In order to determine if the markets will clear I examine the profit functions for fishing vessels under all four scenarios. These are shown in Figures 4.10, 4.11, 4.12 and 4.13.

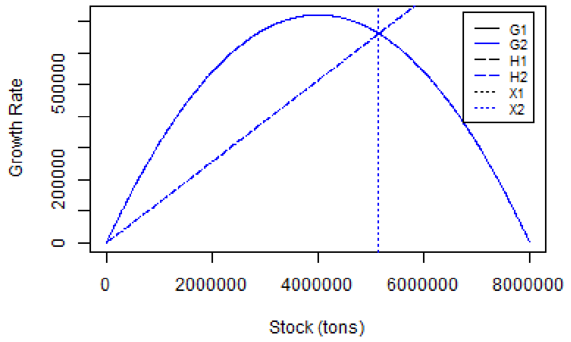


Figure 4.7: The equilibrium steady state levels for $K = 8$ million in black and $K = 8$ million in blue.

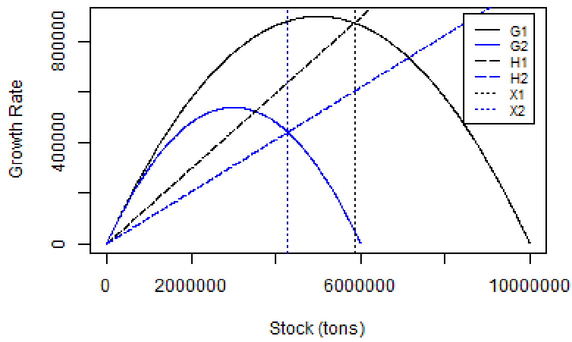


Figure 4.8: The equilibrium steady state levels for $K = 10$ million in black and $K = 6$ million in blue.

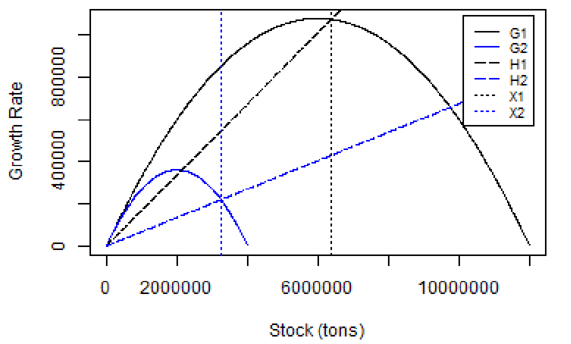
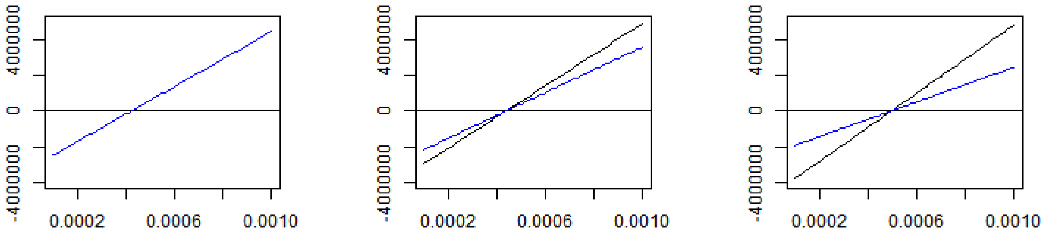
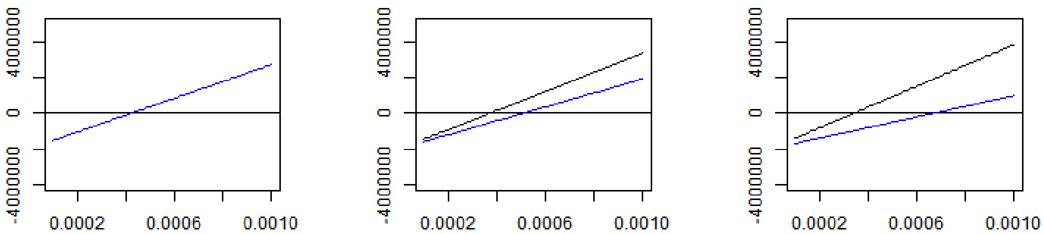


Figure 4.9: The equilibrium steady state levels for $K = 12$ million in black and $K = 4$ million in blue.



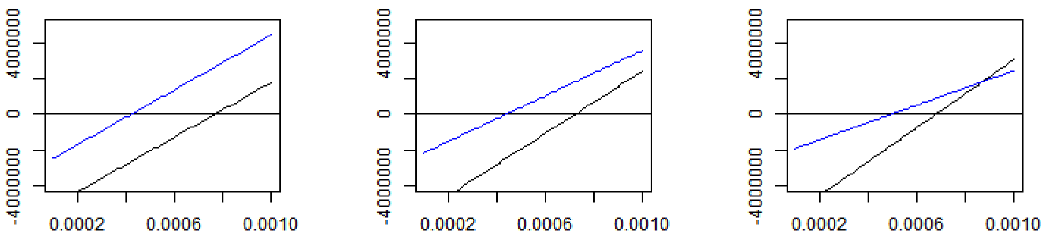
(a) $K_i = 8$ mil, $K_j = 8$ mil (b) $K_i = 10$ mil, $K_j = 6$ mil (c) $K_i = 12$ mil, $K_j = 4$ mil

Figure 4.10: Full Overlap - Input Regulation for K_i (black) and K_j (blue)



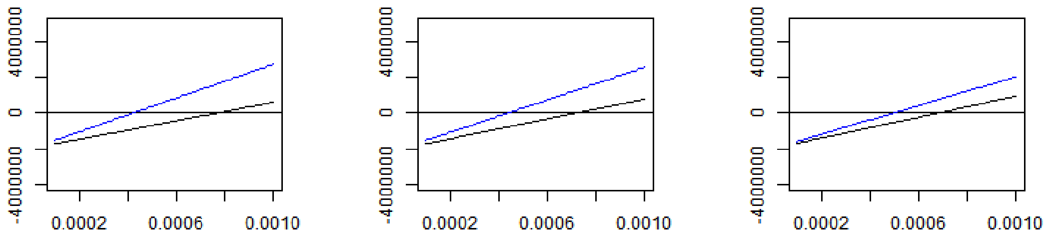
(a) $K_i = 8$ mil, $K_j = 8$ mil (b) $K_i = 10$ mil, $K_j = 6$ mil (c) $K_i = 12$ mil, $K_j = 4$ mil

Figure 4.11: Full Overlap - Output Regulation for K_i (black) and K_j (blue)



(a) $K_i = 8$ mil, $K_j = 8$ mil (b) $K_i = 10$ mil, $K_j = 6$ mil (c) $K_i = 12$ mil, $K_j = 4$ mil

Figure 4.12: Full Separation - Input Regulation for K_i (black) and K_j (blue)



(a) $K_i = 8$ mil, $K_j = 8$ mil (b) $K_i = 10$ mil, $K_j = 6$ mil (c) $K_i = 12$ mil, $K_j = 4$ mil

Figure 4.13: Full Separation - Output Regulation for K_i (black) and K_j (blue)

For both management schemes under full overlap, it is clear that unless the two countries are identical as in 4.10a and 4.11a, the larger country is more profitable than the smaller country. For input regulation under full overlap, in 4.10b and 4.10c the market will clear since both countries are profitable above $\bar{q}$. However, efficient ordering is not guaranteed. For output regulation cases under full overlap shown in Figure 4.11, there are different values for $\bar{q}$ for each country, and the larger country i is always more profitable. This means that it may not be possible for the license market to clear, and it is impossible for efficient ordering to occur because $\bar{q}_i > \bar{q}_j$.

For input regulation and output regulation under full separation, the smaller country is more profitable than the larger country, as shown in Figure 4.12 and 4.13. This is due to the higher price being charged for the larger country licenses relative to the full overlap cases, which is a reflection of the condition that $\bar{q}_i > \bar{q}_j$ in the harvest function. For input regulation cases under full separation in Figure 4.12a and 4.12b, the market may be able to clear, however this is highly unlikely unless the less productive fishing vessels buy licenses first. The case in Figure 4.12c is the only candidate where where the market can clear and efficient ordering achieved without any license sales conditions. Finally for output regulation under full separation, figure 4.13a, 4.13b and 4.13c may all achieve market clearing and efficient ordering if less productive fishing vessels are allowed to buy licenses first. Without this condition the markets may not clear.

4.4 Policy Implications

The first policy implication is that support for a switch from the current VDS to a output based scheme may no longer be relevant. In fact, it may be in the interest of the PNA to continue with the VDS rather than switch to quota based regulation. This will depend on the constant cost of fishing assumption. If the costs of fishing over different member countries is the same, then the PNA may be better off retaining the VDS. However, if the cost of fishing over different countries are significantly different, then output based quota regulation could potentially yield the same results, but with higher revenue. Given that that the PNA is a single large fishery based in the same ocean, the only significant differences in cost between each country could be from the distances required to travel to each country.

The second policy implication is that the PNA should continue to set modest harvest targets, and consider a safety margin for the number of licenses that it sells. This is because the analysis suggest that the conditions required for the a fishery manager to hit the exact harvest targets are very specific, and hence unlikely to occur. This implies that it is more likely that the harvest targets set by the PNA are either not met, or exceeded. Furthermore, the analysis suggests that this experience is likely to be different for each of the countries. There is anecdotal evidence indicating that this is the real world experience for the PNA, where some countries are unable to sell all of their licenses, while other have excess demand for their licenses and are pressured to sell more licenses than they are allocated.

This leads to the third policy implication, which is that the PNA should examine current licenses sales arrangements and pricing mechanisms to see if improvements can be made in terms of ensuring that at least markets clear. The PNA is a coalition of eight countries, and so an analysis based on the methodology used this study will be very complicated. In addition to this, licenses are sold using auctions which are complex and notoriously difficult to correctly implement. A first step may be to use empirical data to examine fishing vessels incentives to examine if pricing mechanisms can be modified to improve license sales, particularly of the smaller countries.

The final policy implication is that it may the best interest of all of the countries to sell the licenses as a group. This conclusion is drawn by examining the single and multi-country models together. Clearly, the single country case is much simpler and does not have any of the additional price dynamics as the multi-country case. An important consideration with a single license is how to share the revenue. There are several prominent mechanisms, however they are complex and would be very difficult to apply in practice.

4.5 Conclusion

In this chapter, I introduce the two country case for the hetergeneous model, based on the multi-patch model from Sanchirico and Wilen. Fishing vessels decide between which countries to buy licenses from, and fishing vessel licenses are specific to each country. The overall goal of this study is to compare an input regulation fishery management scheme to a quota based management scheme, for a cooperatively owned and managed fishery. The primary variables for comparison are the stock levels, harvest size, rent levels, and the revenue levels to each country. The distribution of each of these variables is a key consideration in this multi-country setting.

One clear implication of including heterogeneous fishing agents, is that in order to correctly characterize the dynamics of the fishery, every fishing vessel's incentives have to be accounted for. I consider two price setting methods for both input and output regulation, and I examine whether the target stock, harvest, and revenue levels set by the manager can be achieved in each of these four cases. This study demonstrates that multi-patch management is more complex that previously thought, and that the management scheme employed is critically important to achieving the goals of the fishery manager.

This study has four primary results. First, under input regulation the license market will clear under the full overlap case. However, an efficient ordering of fishing vessels over the two countries is not guaranteed. Second, full efficiency is possible for input regulation under full separation, but this result may be achievable only under specific conditions. Third, output regulation under full overlap is not supportable under the assumptions made in this study. Finally, output regulation under full separation could theoretically achieve the market clearing condition and efficient ordering condition. However, this is highly unlikely to occur without intervention from the manager and assuming perfect information. The last two results suggest that output regulation is not feasible. However, relaxing the assumption of constant cost over both countries could change this result.

The first result of the simulation is that both full overlap and full separation yield the same harvest rate, steady state stock levels, and total combined rent and effort levels. The simulation also suggest that potential revenue under output regulation is higher relative to input regulation. This is true for all cases under the heterogeneous model. This result extends from and reinforces the same result from the single country case. The simulation results show that output regulation may not achieve the market clearing condition under both full overlap and full separation, and efficient ordering is not possible at all under full overlap.

One interesting outcome from this simulation exercise is that under full overlap, the larger country is more profitable, primarily due to the higher stock level. However, under full separation the smaller country is more profitable than the larger country. This is due to the higher license prices that are charged for the larger country's licenses eroding the advantage of a larger stock size.

The primary contribution of this paper is that it examines the welfare problem for a revenue maximizing fishery coalition, comparing input versus output based regulation, achieved by introducing heterogeneity into the multi patch bio-economic model. The motivating problem for this analysis is also novel. To the author's knowledge the specific problem of the PNA fishery outlined in this multi-country context has yet to be explored within the literature. The potential impacts of such an analysis on policy could be significant for the member countries of the PNA. A weakness of the analysis is that the linear profit function assumption plays an important role in the results. This assumption means that profit levels in output regulation are dependent only on stock size and license prices, not productivity. This implies that fishing vessels with a higher productivity level have no advantage under output regulation. Coupled with the constant cost assumption, this drives the negative results of output regulation. These could be areas for improvement in future studies.

Appendix 3

4.A Standard Model

Assume there are m countries. Each country has a separate stock in a spatial environment, which can be treated as a patch. Stock size X for country i evolves according to

$$\dot{X}_i = g_i(X_i) - h_i(X_i, E_i) - d_i X_i + \sum_{j=1, j \neq i}^{m} d_{ji} X_j \tag{4.56}$$

subject to

$$X_i(0) = X_0, \quad X_j(0) = X_0, \quad E_i(0) = E_0, \quad E_j(0) = E_0, \quad t \geq 0$$

$$X_i(t) \geq 0, \quad X_j(t) \geq 0, \quad E_i(t) \geq 0, \quad E_j(t) \geq 0$$

where $g(X)$ is a logistic growth function for the stock of fish X, and $h(X, E_t)$ is a harvest function which depends on the stock level and effort level E applied to the fishery. Effort E for country i is a function of the net revenues available in each country, and evolves according to

$$\dot{E} = \delta_i [p h_i(X_i, E_i) - cE_i] + \sum_{j=1, j \neq i}^{m} \delta_{ji} [p h_i(X_i, E_i) - cE_i - p h_j(X_j, E_j) - cE_j] \tag{4.57}$$

subject to the same conditions as in 4.56, where $g_i(X_i) = rX_i(1 - X_i/K)$ is the growth rate and $h_i(X_i, E_i) = q_i X_i E_i$ represents the harvest of tuna from patch i.

In equation 4.56, $d_i X_i \geq 0$ represents the outflow of tuna from country i into other countries, and $d_{ji} X_j \geq 0$ represents the inflow of fish from country j to country i. For tractability I disregard tuna outflows and inflows from international waters. Effort in each country depends on own patch net revenues and elasticity term δ_i, as well as on relative net revenues and the between patch elasticity interactive term between country j and country i, δ_{ji}.

This general model can be used to represent many different scenarios and is considered a fully integrated model (Sanchirico and Wilen 1999). In this general specification there is movement from each patch to all the other patches. Another possible specification is a source-sink model, when there is one way movement from one patch to the other patches. As a simplification, the summation term in equation 4.56 becomes $d_j X_j \geq 0$, and similarly the between patch elasticity interactive term δ_{ji} in equation 4.57 becomes δ_j.

Open Access

For the two country open access case, at equilibrium, the equations of motion for stock X and effort E for each country are equal to zero. For the fully integrated model, these are

$$\dot{X}_i = g_i(X_i) - h_i(X_i, E_i) - d_i X_i + d_j X_j = 0 \tag{4.58}$$

$$\dot{X}_j = g_j(X_j) - h_j(X_j, E_j) - d_j X_j + d_i X_j = 0 \tag{4.59}$$

$$\dot{E}_i = \delta_i(ph_i(X_i, E_i) - cE_i) + \delta_j[(ph_i(X_i, E_i) - cE_i) - (ph_j(X_j, E_j) - cE_j)] = 0 \tag{4.60}$$

$$\dot{E}_j = \delta_j(ph_j(X_j, E_j) - cE_j) + \delta_i[(ph_j(X_j, E_j) - cE_j) - (ph_i(X_i, E_i) - cE_i)] = 0 \tag{4.61}$$

From 4.60 and 4.61, we get:

$$(\delta_i + \delta_j)(ph_i(X_i, E_i) - cE_i) - \delta_j[(ph_j(X_j, E_j) - cE_j)] = 0$$
$$(\delta_j + \delta_i)(ph_j(X_j, E_j) - cE_j) - \delta_i[(ph_i(X_i, E_i) - cE_i)] = 0$$

Using elementary algebra the only solution to this system of equations is

$$pq_i X_i E_i - cE_i = 0$$
$$pq_j X_j E_j - cE_j = 0$$

Under the assumption that $K_i > \frac{c}{pq_i}$ and $K_j > \frac{c}{pq_j}$, the steady state stock size for the two patches under open access are

$$X_i^{OA} = \frac{c}{pq_i} \tag{4.62}$$

$$X_j^{OA} = \frac{c}{pq_j} \tag{4.63}$$

Substituting these back into the equations of motion for stock 4.58 and 4.59, we get expressions for steady state effort levels under open access

$$E_i^{OA} = \frac{1}{q_i}[r_i - d_i + d_j \frac{K_i}{K_i}] - \frac{cr_i}{pK_i q_j^2} \tag{4.64}$$

$$E_j^{OA} = \frac{1}{q_j}[r_j - d_j + d_i \frac{K_j}{K_j}] - \frac{cr_j}{pK_j q_i^2} \tag{4.65}$$

Maximum Sustainable Yield

The logistical growth function is maximized where $g'(X) = 0$, however there are additional interaction terms for inflows and outflows of tuna to other countries to consider as part of total growth of the stocks.

$$g_i(X_i) - d_i X_i + d_j X_j 0$$

$$g_j(X_j) - d_j X_j + d_i X_i$$

Taking the derivative for these yields the MSY equilibrium stock level.

$$X_i^{MSY} = \frac{K_i}{2} - \frac{d_i K_i}{2r} \tag{4.66}$$

$$X_j^{MSY} = \frac{K_j}{2} - \frac{d_j K_j}{2r} \tag{4.67}$$

Substituting this into the equation of motion for stocks (equation 4.58 and 4.59) yields the MSY equilibrium effort level.

$$E_i^{MSY} = \frac{K_i(\frac{r_i}{4} + \frac{d_i^2}{4r_i} - \frac{d_i}{2}) + \frac{d_j K_j}{2}(1 - \frac{d_j}{r_j})}{\frac{q_i K_i}{2}(1 + \frac{1}{r_i})} \tag{4.68}$$

$$E_j^{MSY} = \frac{K_j(\frac{r_j}{4} + \frac{d_j^2}{4r_j} - \frac{d_j}{2}) + \frac{d_i K_i}{2}(1 - \frac{d_i}{r_i})}{\frac{q_j K_j}{2}(1 + \frac{1}{r_j})} \tag{4.69}$$

Optimal Extraction

If both patches were under single ownership, the owner would maximize the effort level expended over both patches according to

$$\max_{E_i, E_j} \int_0^\infty e^{-\rho t}[ph(X_{i,t}, E_{i,t}) - cE_{i,t} + ph(X_{j,t}, E_{j,t}) - cE_{j,t}]dt$$

Subject to:

$$\dot{x}_{i,t} = g(X_{i,t}) - h(X_{i,t}, E_{i,t}) - d_i X_{i,t} + d_j X_{j,t} \tag{4.70}$$

$$\dot{x}_{j,t} = g(X_{j,t}) - h(X_{j,t}, E_{j,t}) - d_j X_{j,t} + d_i X_{i,t} \tag{4.71}$$

$$X_i(0) = X_0, \quad X_j(0) = X_0, \quad E_i \leq E_{max}, \quad E_j \leq E_{max}, \quad t \geq 0$$
$$E_i(t) \geq 0, \quad E_j(t) \geq 0$$

E_{max} is the maximum possible effort days that can be applied to the fishery in a season. This is equal to the number of days in a season for each fishing vessel e_{max} multiplied by the number of vessels N operating in the fishery. That is, $E_{max} = Ne_{max}$.

The current value Hamiltonian for the problem is

$$\begin{aligned} H = ph(X_{i,t}, E_{i,t}) - cE_{i,t} + ph(X_{j,t}, E_{j,t}) - cE_{j,t} + \lambda[g_i(X_{i,t}) - h_i(X_{i,t}, E_{i,t}) - d_i X_{i,t} + d_j X_{j,t}] \\ + \mu[g(X_{j,t}) - h(X_{j,t}, E_{j,t}) - d_{j,t} X_{j,t} + d_i X_{i,t}] \end{aligned}$$

Applying the maximum principle the following conditions are derived

$$\begin{aligned} \frac{\partial H}{\partial E_{i,t}} &= (ph_E(X_{i,t}, E_{i,t}) - c - \lambda h_E(X_{i,t}, E_{i,t}) = 0 \\ \frac{\partial H}{\partial E_{j,t}} &= (ph_E(X_{j,t}, E_{j,t} - c - \lambda h_E(X_{j,t}, E_{j,t}) = 0 \end{aligned} \tag{4.72}$$

$$\begin{aligned} \dot{\lambda} &= \lambda\rho - ph_x(X_{i,t}, E_{i,t}) - \lambda(g_x(X_{i,t}) + h_x(X_{i,t}, E_{i,t}) - d_i) - \mu d_i \\ \dot{\mu} &= \mu\rho - ph_x(X_{j,t}, E_{j,t}) - \mu(g_x(X_{j,t}) + h_x(X_{j,t}, E_{j,t}) - d_j) - \lambda d_j \end{aligned} \tag{4.73}$$

$$\begin{aligned} \dot{x}_{i,t} &= g(X_{i,t}) - h(X_{i,t}, E_{i,t}) - d_i X_{i,t} + d_j X_{j,t} \\ \dot{x}_{j,t} &= g(X_{j,t}) - h(X_{j,t}, E_{j,t}) - d_j X_{j,t} + d_i X_{i,t} \end{aligned} \tag{4.74}$$

At the steady state equilibrium, $\dot{x}_{i,t} = \dot{x}_{j,t} = 0$ and $\dot{\lambda}_t = \dot{\mu}_t = 0$. The conditions above reduce to [1]

[1]These derivations are similar to the heterogeneous case that is presented in Appendix **??**

$$\Big(p - \frac{cE_{q_i}}{h_{q_i}}\Big)\rho = \Big(p - \frac{cE_{q_i}}{h_{q_i}}\Big)g_{x_i} + \frac{cE_{q_i}}{X_{i,t}h_{q_i}}g(X_{i,t}) \tag{4.75}$$

$$\Big(p - \frac{cE_{q_j}}{h_{q_j}}\Big)\rho = \Big(p - \frac{cE_{q_j}}{h_{q_j}}\Big)g_{x_j} + \frac{cE_{q_j}}{X_{j,t}h_{q_j}}g(X_{j,t}) \tag{4.76}$$

From equation 4.75 and 4.76, substituting for $g(X)$ and $h(X, E)$ and rearranging

$$(\frac{2pr}{K})X_{i,t}^2 - (pr - p\rho - \frac{cr}{q_{i,t}K} - \frac{cd_i}{q_{j,t}K})X_{i,t} - \frac{\rho c - cd_i}{q_{i,t}} = 0 \tag{4.77}$$

$$(\frac{2pr}{K})X_{j,t}^2 - (pr - p\rho - \frac{cr}{q_{j,t}K} - \frac{cd_j}{q_{i,t}K})X_{j,t} - \frac{\rho c - cd_j}{q_{j,t}} = 0 \tag{4.78}$$

The solutions for X_i^* and X_j^* takes the following form, which can be positive or negative. This depends on parameters however the positive root is the solution in this case.

$$X_i^* = \frac{-B_i \pm \sqrt{B_i^2 - 4A_iC_i}}{2A_i} \tag{4.79}$$

where

$$A_i = \frac{2pr_i}{K_i}; B_i = pr - p\rho - \frac{cr}{q_{i,t}K} - \frac{cd_i}{q_{j,t}K}; C_i = \frac{\rho c - cd_i}{q_{i,t}}$$

and

$$X_j^* = \frac{-B_j \pm \sqrt{B_j^2 - 4A_jC_j}}{2A_j} \tag{4.80}$$

where

$$A_j = \frac{2pr_j}{K_j}; B_j = pr - p\rho - \frac{cr}{q_{j,t}K} - \frac{cd_j}{q_{i,t}K}; C_j = \frac{\rho c - cd_j}{q_{j,t}}.$$

Substituting equation 4.79 and 4.80 into the equation of motion for stocks (equations 4.70 and 4.71) respectively, yields the optimal equilibrium (steady state) effort levels E_i^* and E_j^*.

$$E_i^* = \frac{r_i}{q_i}(1 - \frac{X_i^*}{K_i}) - \frac{d_i}{q_i} + \frac{d_jX_j^*}{q_iX_i^*} \tag{4.81}$$

$$E_j^* = \frac{r_j}{q_j}(1 - \frac{X_j^*}{K_j}) - \frac{d_j}{q_j} + \frac{d_iX_i^*}{q_jX_j^*} \tag{4.82}$$

The optimal harvest strategy for each country is a piecewise function which depends on the stock level in the fishery. This is a 'bang-bang' type of transition to steady state, and is a result of the infinitely elastic tuna price (constant price) assumption. If the stock level is above the steady state, the optimal harvest rate is to apply maximum effort. At steady state stock levels, the optimal strategy is to apply the effort rate that results in a harvest level equal to the growth rate of the stock. At stock levels below steady state the optimal harvest rate is zero.

$$E_i(t) = \begin{cases} E^{max} & if \quad X_i(t) > X_i^* \\ E_i^* & if \quad X_i(t) = X_i^* \\ 0 & if \quad X_i(t) < X_i^* \end{cases} \tag{4.83}$$

$$E_j(t) = \begin{cases} E^{max} & if \quad X_j(t) > X_j^* \\ E_j^* & if \quad X_j(t) = X_j^* \\ 0 & if \quad X_j(t) < X_j^* \end{cases} \tag{4.84}$$

4.B Optimal Extraction - Full Overlap

$$\begin{aligned}H = p(b^2-\bar{q}^2)\frac{X_ieN_i}{2(b-a)} - ceN_i\Big(\frac{b-\bar{q}}{b-a}\Big) + p(b^2-\bar{q}^2)\frac{X_je(N-N_i)}{2(b-a)} - ce(N-N_i)\Big(\frac{b-\bar{q}}{b-a}\Big)\\ + \lambda\Big[r_iX_i(1-X_i/K_i) - (b^2-\bar{q}^2)\frac{X_ieN_i}{2(b-a)} - d_iX_i + d_jX_j\Big]\\ + \mu\Big[r_jX_j(1-X_j/K_j) - (b^2-\bar{q}^2)\frac{X_je(N-N_i)}{2(b-a)} - d_jX_j + d_iX_i\Big]\end{aligned}$$

Disregarding flows between patches the Hamiltonian is

$$\begin{aligned}H = p(b^2-\bar{q}^2)\frac{X_ieN_i}{2(b-a)} + p(b^2-\bar{q}^2)\frac{X_je(N-N_i)}{2(b-a)} - ceN\Big(\frac{b-\bar{q}}{b-a}\Big)\\ + \lambda\Big[r_iX_i(1-X_i/K_i) - (b^2-\bar{q}^2)\frac{X_ieN_i}{2(b-a)}\Big]\\ + \mu\Big[r_jX_j(1-X_j/K_j) - (b^2-\bar{q}^2)\frac{X_je(N-N_i)}{2(b-a)}\Big]\end{aligned}$$

Applying the maximum principle the following conditions are derived

$$\begin{aligned}\frac{\partial H}{\partial \bar{q}_i} = p(-2\bar{q}\frac{X_ieN_i}{2(b-a)}) + p(-2\bar{q}\frac{X_je(N-N_i)}{2(b-a)}) - c(-eN\frac{1}{b-a}) -\\ \lambda(-2\bar{q}\frac{X_ieN_i}{2(b-a)}) - \mu(-2\bar{q}\frac{X_je(N-N_i)}{2(b-a)}) = 0\end{aligned} \quad (4.85)$$

$$\begin{aligned}\frac{\partial H}{\partial N_i} = p(b^2-\bar{q}^2)\frac{X_ie}{2(b-a)} - ce\Big(\frac{b-\bar{q}}{b-a}\Big) - p(b^2-\bar{q}^2)\frac{X_je}{2(b-a)} + ce\Big(\frac{b-\bar{q}}{b-a}\Big)\\ + \lambda\Big[-(b^2-\bar{q}^2)\frac{X_ie}{2(b-a)}\Big] + \mu\Big[(b^2-\bar{q}^2)\frac{X_je}{2(b-a)}\Big] = 0\end{aligned} \quad (4.86)$$

$$\begin{aligned}\dot{\lambda} = \lambda\rho - p(b^2-\bar{q}^2)\frac{eN_i}{2(b-a)} - \lambda[r_i - \frac{2r_iX_i}{K_i} - (b^2-\bar{q}^2)\frac{eN_i}{2(b-a)}]\\ \dot{\mu} = \mu\rho - p(b^2-\bar{q}^2)\frac{e(N-N_i)}{2(b-a)} - \mu[r_j - \frac{2r_jX_j}{K_j} - (b^2-\bar{q}^2)\frac{e(N-N_i)}{2(b-a)}]\end{aligned} \quad (4.87)$$

$$\begin{aligned}\dot{X}_i = r_iX_i(1-X_i/K_i) - (b^2-\bar{q}^2)\frac{X_ieN_i}{2(b-a)}\\ \dot{X}_j = r_jX_j(1-X_j/K_j) - (b^2-\bar{q}^2)\frac{X_jeN_j}{2(b-a)}\end{aligned} \quad (4.88)$$

From MP1

$$\lambda = p - \frac{c}{\bar{q}X_i}$$

$$\mu = p - \frac{c}{\bar{q}X_j}$$

From MP3, applying the steady state condition $\dot{X}_i = 0$ and $\dot{X}_j = 0$ I get

$$r_i - \frac{r_i X_i}{K_i} = (b^2 - \bar{q}^2)\frac{eN_i}{2(b-a)}$$

$$r_j - \frac{r_j X_j}{K_j} = (b^2 - \bar{q}^2)\frac{e(N - N_i)}{2(b-a)}$$

Applying the steady state condition $\dot{\lambda} = 0$ and $\dot{\mu} = 0$ to MP2

$$\lambda\rho = p(r_i - \frac{r_i X_i}{K_i}) + \lambda[r_i - \frac{r_i X_i}{K_i}]$$

$$\mu\rho = p(r_j - \frac{r_j X_j}{K_j}) + \mu[r_j - \frac{r_j X_j}{K_j}]$$

After substitution this gives me the tranversality condition, which along with the equation of motion for the fishery forms a set of equations which can solve for $\bar{q}, X_i$ and X_j.

$$(p - \frac{c}{\bar{q}X_i})\rho = p(r_i - \frac{r_i X_i}{K_i}) + (p - \frac{c}{\bar{q}X_i})[r_i - \frac{r_i X_i}{K_i}]$$

$$(p - \frac{c}{\bar{q}X_j})\rho = p(r_j - \frac{r_j X_j}{K_j}) + (p - \frac{c}{\bar{q}X_j})[r_j - \frac{r_j X_j}{K_j}]$$

which after rearranging becomes

$$X_i^2 \frac{2pr_i}{K_i} + X_i\Big(p\rho - pr_i - \frac{cr_i}{K_i\bar{q}}\Big) + \frac{cr_i}{\bar{q}} = 0 \tag{4.89}$$

$$X_j^2 \frac{2pr_j}{K_j} + X_j\Big(p\rho - pr_j - \frac{cr_j}{K_j\bar{q}}\Big) + \frac{cr_j}{\bar{q}} = 0 \tag{4.90}$$

The solution for X_i^* takes the following form.

$$X_i^* = \frac{-B_i \pm \sqrt{B_i^2 - 4A_iC_i}}{2A_i} \tag{4.91}$$

where

$$A_i = \frac{2pr_i}{K_i}; B_i = p\rho - pr_i - \frac{2cr_i}{K_i\bar{q}}; C_i = \frac{cr_i}{\bar{q}}$$

and

$$X_j^* = \frac{-B_j \pm \sqrt{B_j^2 - 4A_jC_j}}{2A_j} \tag{4.92}$$

where

$$A_j = \frac{2pr_j}{K_j}; B_j = p\rho - pr_j - \frac{2cr_j}{K_j\bar{q}}; C_j = \frac{cr_j}{\bar{q}}$$

4.C Optimal Extraction - Full Separation

$$H = p(b^2 - \bar{q}_i^2)\frac{X_i eN}{2(b-a)} - ceN\Big(\frac{b-\bar{q}_i}{b-a}\Big) + p(\bar{q}_i^2 - \bar{q}_j^2)\frac{X_j eN}{2(b-a)} - ceN\Big(\frac{\bar{q}_i - \bar{q}_j}{b-a}\Big)$$
$$+ \lambda_t\Big[r_i X_i(1 - X_i/K_i) - (b^2 - \bar{q}_i^2)\frac{X_i eN}{2(b-a)} - d_i X_i + d_j X_j\Big]$$
$$+ \mu_t\Big[r_j X_j(1 - X_j/K_j) - (\bar{q}_i^2 - \bar{q}_j^2)\frac{X_j eN}{2(b-a)} - d_j X_j + d_i X_i\Big]$$

Disregarding flows between patches

$$H = p(b^2 - \bar{q}_i^2)\frac{X_i eN}{2(b-a)} - ceN\Big(\frac{b-\bar{q}_i}{b-a}\Big) + p(\bar{q}_i^2 - \bar{q}_j^2)\frac{X_j eN}{2(b-a)} - ceN\Big(\frac{\bar{q}_i - \bar{q}_j}{b-a}\Big)$$
$$+ \lambda_t\Big[r_i X_i(1 - X_i/K_i) - (b^2 - \bar{q}_i^2)\frac{X_i eN}{2(b-a)}\Big]$$
$$+ \mu_t\Big[r_j X_j(1 - X_j/K_j) - (\bar{q}_i^2 - \bar{q}_j^2)\frac{X_j eN}{2(b-a)}\Big]$$

Applying the maximum principle the following conditions are derived

$$\frac{\partial H}{\partial \bar{q}_i} = -\frac{p\bar{q}_i X_i eN}{b-a} + \frac{ceN}{b-a} + \frac{p\bar{q}_i X_j eN}{(b-a)} - \frac{ceN}{b-a} + \lambda\frac{\bar{q}_i X_i eN}{b-a} - \mu\frac{\bar{q}_i X_j eN}{(b-a)} = 0 \tag{4.93}$$

$$\frac{\partial H}{\partial \bar{q}_j} = -\frac{p\bar{q}_j X_j eN}{b-a} + \frac{ceN}{b-a} + \mu\frac{\bar{q}_j X_j eN}{b-a} = 0 \tag{4.94}$$

$$\begin{aligned}\dot{\lambda} &= \lambda\rho - p(b^2 - \bar{q}_i^2)\frac{eN}{2(b-a)} - \lambda[r_i - \frac{2r_i X_i}{K_i} - (b^2 - \bar{q}_i^2)\frac{eN}{2(b-a)}] \\ \dot{\mu} &= \mu\rho - p(\bar{q}_i^2 - \bar{q}_j^2)\frac{eN}{2(b-a)} - \mu[r_j - \frac{2r_j X_j}{K_j} - (\bar{q}_i^2 - \bar{q}_j^2)\frac{eN}{2(b-a)}]\end{aligned} \tag{4.95}$$

$$\begin{aligned}\dot{x}_i &= r_i X_i(1 - X_i/K_i) - (b^2 - \bar{q}_i^2)\frac{X_i eN}{2(b-a)} \\ \dot{x}_j &= r_j X_j(1 - X_j/K_j) - (\bar{q}_i^2 - \bar{q}_j^2)\frac{X_j eN}{2(b-a)}\end{aligned} \tag{4.96}$$

From MP1

$$\lambda = p - \frac{c}{\bar{q}_j X_i} \tag{4.97}$$

$$\mu = p - \frac{c}{\bar{q}_j X_j} \tag{4.98}$$

From MP3, applying the steady state condition $\dot{x}_i = 0$ and $\dot{x}_j = 0$ we get

$$r_i - \frac{r_i X_i}{K_i} = (b^2 - \bar{q}_i^2)\frac{X_i eN}{2(b-a)}$$

$$r_j - \frac{r_j X_j}{K_j} = (\bar{q}_i^2 - \bar{q}_j^2)\frac{X_j eN}{2(b-a)}$$

Applying the steady state condition $\dot{\lambda} = 0$ and $\dot{\mu} = 0$ to MP2 yields

$$\lambda\rho = p(b^2 - \bar{q}_i^2)\frac{eN}{2(b-a)} + \lambda[r_i - \frac{2r_i X_i}{K_i} - (b^2 - \bar{q}_i^2)\frac{eN}{2(b-a)}]$$

$$\mu\rho = p(\bar{q}_i^2 - \bar{q}_j^2)\frac{eN}{2(b-a)} + \mu[r_j - \frac{2r_j X_j}{K_j} - (\bar{q}_i^2 - \bar{q}_j^2)\frac{eN}{2(b-a)}]$$

which after substitution and rearranging, the following steady state conditions are found.

$$\rho\Big(p - \frac{c}{\bar{q}_j X_i}\Big) = p\Big(r_i - \frac{r_i X_i}{K_i}\Big) + \Big(p - \frac{c}{\bar{q}_j X_i}\Big)\Big[-\frac{r_i X_i}{K_i}\Big]$$

$$\rho\Big(p - \frac{c}{X_j \bar{q}_j}\Big) = p\Big(r_j - \frac{r_j X_j}{K_j}\Big) + \Big(p - \frac{c}{X_j \bar{q}_j}\Big)\Big[-\frac{r_j X_j}{K_j}\Big]$$

which after rearranging becomes

$$X_i^2\Big[\frac{2pr_i}{K_i}\Big] - X_i\Big[p\rho - pr_i - \frac{cr_i}{\bar{q}_j K_i}\Big] + \frac{c\rho}{\bar{q}_j} = 0$$

$$X_j^2\Big[\frac{2pr_j}{K_j}\Big] + X_j\Big[p\rho - pr_j - \frac{cr_j}{\bar{q}_j K_j}\Big] + \frac{c\rho}{\bar{q}_j} = 0$$

The solution for X_i^* takes the following form, which can be positive or negative. The positive root is the solution in this case. For country i,

$$X_i^* = \frac{-B_i \pm \sqrt{B_i^2 - 4A_i C_i}}{2A_i}$$

where

$$A_i = \frac{2pr_i}{K_i}$$

$$B_i = p\rho - pr_i - \frac{cr_i}{\bar{q}_j K_i}$$

$$C_i = \frac{c\rho}{\bar{q}_j}$$

For country j,

$$X_j^* = \frac{-B_j \pm \sqrt{B_j^2 - 4A_j C_j}}{2A_j}$$

where

$$A_j = \frac{2pr_j}{K_j}$$

$$B_j = p\rho - pr_j - \frac{cr_j}{\bar{q}_j K_j}$$

$$C_j = \frac{c\rho}{\bar{q}_j}$$

Chapter 5

A Revenue Sharing Mechanism for a Tuna Cartel: Local vs Global Licenses

5.1 Introduction

In this paper I analyze two approaches to revenue sharing for a coalition of seven tuna rich countries in the central-eastern Pacific Ocean. This coalition is known as the Parties to the Nauru Agreement (PNA), and was formed in order to achieve greater bargaining power and management over the fisheries resources in its EEZ. The first approach is what I refer to as partial cooperation, and is the approach that the PNA currently employs. Under partial cooperation the number of total licenses is set together then distributed to members to sell individually. The second approach which I introduce in this paper is what I consider to be a full cooperation approach, and is where the total number of licenses are set and sold together as one entity. I will refer to this as the full cooperation approach. These two approaches are mechanisms that are used to share the revenue from the cooperative management of the tuna fishery. The primary objective of this study is to compare these two mechanisms in order to characterize the benefits and drawbacks of switching to full cooperation.

There are a few points to note about the general approach taken in this study. First, only the welfare of the member countries in the PNA is considered. The model is fairly complex even without considering the welfare of fishing vessels, and so this will keep the analysis as simple as possible. This also serves to focus the results of the study on the policy implications to the PNA and the member countries. Second, the results from this study only reflect the design of each approach, and are independent of any market power considerations. This was achieved by the choice of the demand function employed in the study. These results therefore serve as a minimum benchmark for what can be achieved by switching to full cooperation, as the inclusion of market power gains reinforce the results of the study. An implication of this is that I assume perfect information, in order to characterize this benchmark. Thirdly, given that the PNA has been in existence for almost four decades, I assume that the PNA as a coalition is inherently stable. As such, analysis of the stability of the coalition is not an important consideration in this study.

The central and eastern areas of the Pacific ocean have the most productive tuna fisheries in the region. These include countries that are signatories to the Parties to the Nauru Agreement (PNA), a coalition of eight Pacific Island Countries (PICs) known to be rich in tuna resources. The returns from these fisheries represent a significant source of income for the PNA members. In 2007 the PNA introduced the Vessel Day Scheme (VDS), an effort or input based management scheme. Under the VDS, licenses to fish in PNA exclusive economic zones (EEZ) are sold on a 'per-day effort' basis. A license gives fishing vessels the right to fish for one day, or 24 hours. As a coalition the PNA sets the total allowable catch (TAC) to be harvested in their combined EEZ. An estimated total allowable effort (TAE) level is then determined which would yield the TAC. Each member country is assigned a proportion of the TAE, or the total number of fishing days in a season. From this point forward, I will refer to this as the share of TAC for each member country.

Licenses to fish are currently sold by individual countries to distant water fishing nation (DWFN) fishing vessels in per day effort units. Under the current arrangement the PNA sets the total allowable catch (TAC) as a coalition. The TAC determines the total harvest, and in turn the total number of effort days or licenses to be sold. This decision is made every few years during a meeting attended by leaders of each member country. In some cases the TAC for the current year is provisionally adopted for the next few years. For example, the PNA set the TAC for 2017 as the same tentative TAC for 2018 and 2019. Licenses are then distributed to each country who sells its licenses individually. The licenses are distributed according to shares based primarily on historical catch, predictions of the future stock size and distribution of fish over the member countries, and likely also includes some level of political considerations. Political considerations aside, these predictions are not completely accurate, and it is one of the reasons the PNA usually sets tentative TAC and shares for a few years at a time. In a sense these tentative shares are an approximation of an average share, which is likely to be a more accurate prediction than specific catch share rates. The licenses are specific to each country and are therefore heterogeneous or local. This arrangement represents only partial cooperation as countries are still competing with each other by selling local licenses.

Since the implementation of the VDS in 2007, total revenue to the coalition as a whole improved dramatically relative to pre-VDS. However, revenue to smaller member countries have been relatively low and volatile from year to year, with some countries failing to sell all of its licenses. The basic intuition behind why this occurs is that the current method of distributing TAC shares is essentially based on an average approximation of predicted stock shares in each country. However, since licenses are specific to each country, the sale of licenses in each country is dependent on actual realized stock shares. Any discrepancies between the the average and realized shares results in some countries having a shortage of licenses, while others will have excess licenses. In order to mitigate this issue, the PNA has allowed licenses to be traded across countries, so that countries with excess licenses can still receive some revenue by selling licenses to countries with excess demand. However, license trading in this manner will not yield as much revenue to the original selling country as direct sales to fishing vessels. An independent review of the VDS requested by the PNA by Anarson (2014) recommended that a study considering the costs and benefits of single license over multiple countries be conducted. The review also recommended that the PNA consider long term share levels rather than year to year revisions.

One attractive feature of this mechanism is that it gives each country full control over the sale of the licenses, and by extension the amount of fishing in its EEZ. Not only can countries safeguard against overfishing, this independence ensures countries are fully insulated from other members in terms of the finances related to the revenue from license sales. In addition, this control over the license sales may be a useful tool in the diplomatic relationships of individual PNA countries with DWFN countries. The current mechanism is also well established, with a proven record of decision making which has provided stability for the coalition over the last two decades. This is a significant point, as the PNA is a rare example of a successful multinational cooperative managing a renewable resource such as a fishery (Bernadett 2014).

The single largest drawback to the current partial cooperation mechanism is the loss of revenue resulting from the excess demand for licenses in some countries, and excess supply in other countries. This is caused by the discrepancy in the shares of the TAC which is distributed to each country, and the actual distribution of the stock of fish over the countries. This also explains why some countries may have been tempted to sell more licenses than they were allocated, and why some end up with unsold licenses. The second disadvantage of partial cooperation is the dependence of the revenue on the volatility of the share of fish stock in each country in each year. This is a problem even under the best case scenario where the TAC shares are revised correctly to match the distribution of tuna stock. Revenue volatility was a key concern for at least one of the PNA countries during consideration of the VDS (Deiye 2007). The third major drawback of partial cooperation, is the competition between countries to sell licenses. This competition erodes the market power of the PNA, and is contrary to the idea of a coalition which strives to replicate a monopoly market. This implies that revenue received by each country can be improved by simply removing this competition between members. This last aspect is not included in the analysis, as the focus is to characterize a minimum benchmark of improvement based solely on the the design of the sharing mechanisms themselves.

In this study I introduce a full cooperation approach, where the PNA sets the TAC over multiple years, and sells the licenses as one entity. The primary point of difference is that these licenses can be used in any EEZ, and are therefore homogeneous or global. This means that one license will give fishing vessels access to all countries in the coalition. It turns out that having a single license not only smooths out revenue from license sales, but also ensures that any excess supply or demand for individual countries is eliminated. All of the licenses can be sold because a single license allows fishing vessels to move freely among each country based on the actual distribution of fish stocks. This is an important point and is where the majority of the gains in revenue over partial cooperation come from. I show that unless each country's share of the stock of fish remains constant from year to year, full cooperation always yields equal to or greater revenue levels relative to partial cooperation. In addition, revenue levels to each country will be stable from year to year, which is another key advantage to this approach. This is primarily due to the licenses being all sold, but also because the share for each country is constant over the number of periods the TAC is decided.

To illustrate the difference between partial and full cooperation, and to understand the intuition behind the results, consider the simplest possible example of the model which is for two countries (A and B) in two periods. This example is outlined in Table 5.1, and forms a basic model which can be extended to multiple countries and multiple time periods.

In period 1, country A has a 20 percent share of the total fish stock, which is denoted by $\alpha_1^A = 0.20$, and 30 percent share of the total fish stock in period 2 which is denoted by $\alpha_2^A = 0.30$. Under both partial cooperation and full cooperation, the TAC is distributed between members according to an expected average share based on the α's, which is

Table 5.1: Illustration of difference in shares for partial cooperation and full cooperation

	$t = 1$	$t = 2$	$t = 1, t = 2$
Country A	$\alpha_1^A = 0.20$	$\alpha_2^A = 0.30$	$\beta_A = 0.25$
Country B	$\alpha_1^B = 0.80$	$\alpha_2^B = 0.70$	$\beta_B = 0.75$

constant for both period 1 and period 2. For country A, this is equal to $\beta_A = 0.25$. Since there are only two countries, the shares for country B are the complement of country A. In period 1, country B has $\alpha_1^B = 0.80$ share of the total fish stock, and in period 2 it has $\alpha_2^B = 0.70$ share of the fish stock. This means the share of the TAC is $\beta_B = 0.75$ for country B.

Note that in period 1, the share of the TAC that country A receives is $\beta_A = 0.25$, but the actual realized share of the total stock of fish is equal to $\alpha_1^A = 0.20$ in period 1. Similarly, in period 1 country B receives $\beta_A = 0.75$ of the TAC, but $\alpha_1^B = 0.80$ of the total stock of fish. Under the assumption of perfect competition among member countries selling licenses, setting the TAC and the number of licenses is the same as setting a single market price for the licenses. For a given market price, fishing vessels buy licenses based on the abundance of fish which is represented by the proportion of the stock of fish in each country. However, in this example there is clearly a discrepancy between the the share of the TAC each country receives, and the proportion of the total stock of fish that each country has. This discrepancy is where the inefficiency in partial cooperation comes from.

Under partial cooperation, in period 1 country A will end up with a surplus of licenses because it receives a higher share of the TAC that the total fish stock share in it's EEZ. By the same logic, country B will end up with excess demand for licenses because it has a higher share of the total fish stock in its EEZ than the share of the TAC that it receives. In period 2, the situation reverses, with country A running out of licenses and country B not able to sell all of its licenses. Under full cooperation both countries receive the same share of TAC as in partial cooperation. However, since there is a single license which allows vessels access to both countries, the distribution of fish stocks does not matter to the sale of the licenses, and so all the licenses will be sold.

In this example I have assumed for tractability that the distribution of the TAC over the two periods is identical under partial and full cooperation. Given the tentative setting of the shares over multiple years, this probably represents the situation in the real world. However, it is also possible that the shares could be adjusted to correctly match the actual distribution of fish stocks. In this case the model predicts that total revenue to the coalition is identical in each period and for the total number of periods, for both partial and full cooperation. However, revenue to each country in each period will fluctuate under partial cooperation relative to full cooperation.

This study has four primary results. The first result is that full cooperation will always result in a more stable income stream relative to partial cooperation. Two exceptions to this result are when the share of fish stock in each country remains stable from year to year, or if full cooperation is implemented in a single year rather than over multiple years. In these two cases the revenue streams will be identical under partial cooperation. The second result is that if the total stock of fish to the coalition remains stable from year to year, total revenue to each country over all periods is always greater under full cooperation. If total stock levels were to fluctuate significantly, it is possible that partial cooperation could yield higher revenue levels relative to full cooperation. However, I show that the degree to which the total stock levels need to vary from year to year for this situation to occur is considerable. For such a large fish stock such as the PNA, it is unlikely to occur unless there is a collapse of the fish stocks. The third result is that total income to the coalition for each individual period for full cooperation will always be equal to or greater than partial cooperation, only if the demand function is convex or linear. If the demand function is concave, then partial cooperation could yield higher total income relative to full cooperation. This result implies that the concavity or convexity of the demand function for licenses plays an important role in the degree of the difference in the revenue between the two functions. For very concave demand functions, countries are always better off under partial cooperation. The final result is that risk averse countries will always prefer full cooperation to partial cooperation. I show that full cooperation second order stochastically dominates partial cooperation. This implies that on average, income from full cooperation will be higher than partial cooperation.

One key advantage of the proposed approach is that the sharing rule used in the current arrangement is retained, minimizing departure from the current approach. This point helps justify dropping coalition stability from this analysis. From a mechanism design perspective, this sharing mechanism is simple and intuitive. While there are several prominent and well established sharing mechanisms which could potentially work, they are generally very complex and difficult to implement in real world applications. For example, the Shapley-value (Shapley 1953) calculates the share of benefits for each member of a coalition as the average of the marginal contribution of that member to every possible combination of the coalition which it is included. Such a complex sharing mechanism would be difficult to explain, let alone justify its adoption, to policy makers.

The primary disadvantage of the full cooperation approach is that countries will lose the ability to control the sale of the licenses and the amount of fishing in its EEZ. Firstly considering the issue of control over licenses sales, from a political standpoint giving up the ability to control the sale of licenses may be important for some of the larger countries who do not have significant problems with revenue fluctuations. Although the option still remains for shares to be distributed as licenses under full cooperation, the price for all licenses will be the same and so it is equivalent to receiving a share of the revenue. Theoretically there is no reason to sell licenses individually as it would only involve costs of individual sale by each country. However, politically there may be value in each country retaining control of it finances. It may also serve as transition step to full revenue sharing. In the presentation of the model and the rest of this section I reference only revenue shares, but the retention of licenses shares is considered in the discussion section.

The second and perhaps more concerning issue is that countries will not be able to control the amount of fishing in its EEZ, which could cause overfishing problems. However, because the stock is jointly managed by setting the TAC together, as long as the TAC is not exceeded by countries selling more licenses than they were allocated, this should not be an issue. In this study I assume that there is a positive relationship between the share of fish stock and the amount of fishing in each country. In addition, the cost of fishing between each country is the same, and that the quality of the fish remains constant in all countries. That implies fishing vessels will fish proportionately the same amount as the shares of each country. One important point to note is that all countries share the stocks. This means that any overfishing in one country is likely to impact the others. The proposed approach at least ensures that smaller countries are compensated for any overfishing in any of the other EEZ.

Another limitation with the full cooperation approach, is that it relies on a fairly accurate estimate of the stock of fish in each country. In this respect however, it is no different from the current partial cooperation approach. For the model I make the strong assumption that the stock level and distribution of fish is known with some certainty from year to year. This to some extent reflects how the PNA sets its TAC tentatively from year to year. This tentative TAC implies that there is room to allow for uncertainty. Given that the intention of this study is to compare both approaches under ideal conditions, I assume that stock levels are known with certainty. Relaxing this assumption could be an important area for future expansion of the model.

In the model I assume that the stock of skipjack migrate between the waters of each of the countries in the PNA, and are therefore common to the majority of the coalition. I do not consider significant source-sink effects from some countries to others, which would impact the dynamics of the sharing mechanism. For simplicity I assume a single stock, and that each country has a share α of the stock in each time period. I also assume that there is a single large fishing fleet which can buy licenses from any of the countries. Throughout the paper, I will refer to a large country as a country with the larger stock and vice versa for a smaller country. The total number of time periods that the coalition sets the TAC is denoted as T. Each individual time period is denoted as t. I examine revenue levels for each country for each single t period as well as for all T periods. Similarly, I examine revenue to the entire coalition for each single t period, as well as for all T periods.

The general form of the demand function adopted in this paper allows for representation of convex, linear and concave demand functions, while retaining the intercepts in all cases. This allows for convenient comparison of the revenue levels for different demand conditions. The results show that the concavity or convexity of the demand function play an important role in determining the degree of difference between the two mechanisms. One of the important assumptions made in this study is that the demand functions for the coalition and each individual country have the same vertical intercept and the same slopes. This implies that each individual country has the same market power as the coalition. This means that the revenue potential to the coalition and each individual country is the same under both approaches, which enables the comparison between the two approaches to be as objective as possible by disregarding any market power gains from the new approach. While this assumption may reflect the case for larger countries which have significantly larger shares relative to the smaller countries, it is unlikely that this is the case for smaller countries. This implies that there will be additional gains in revenue specifically from market power for the full cooperation approach relative to partial cooperation, which reinforce the findings in this analysis.

Under both mechanisms, demand for licenses is determined by the distribution of stock among countries and supply is determined by the amount of licenses each country has to sell. Since all licenses are assumed to be sold in the beginning of the season, all fishermen have access to the same information. Along with the assumption that all countries have the same market power, this means there is a single price for all licenses. This means that the model closely resembles a Cournout market structure. In practice licenses are sold by each PNA country throughout the year at non specified intervals, which implies that fishing vessels can receive different information and so prices can adjust. However given the goals of the study and the fact that the market does not clear in practice, this is a reasonable compromise.

When examining coalitions, stability is usually an important consideration. The PNA has now been existence for more than two decades, and endured several deviations from the coalition rules by members. For this study I assume that the PNA is inherently stable (Yeeting et al. 2018) and so I focus on showing that the revenue under full cooperation is at least as good as revenue under partial cooperation.

This study contributes to the literature in three ways. The first contribution is from comparing mechanisms for the management and revenue sharing of a renewable resource using local versus global licenses. Licenses allowing the exploitation of a natural resource are not unique to fisheries. However the cooperative management of a natural resource which can move over time is not readily found in other industries. This leads to the question of whether there should be a single cooperative level global license, or as in the case of the PNA individual local licenses. Some examples of resource right licenses sold in the literature are mining prospecting licenses and radio spectrum licenses. Like the PNA licenses, radio spectrum licenses (Milgrom 1998, McMillan 1994) and mining licenses (Cramton 2007) are sold using auctions. However that is where similarities end as neither of these licenses have been examined in the context of local versus global rights.

The second contribution is this idea of partial cooperation within cooperative games. Partial cooperation falls in both cooperative and non-cooperative fields. As far as the author is aware this specific type of structure has not been examined before. OPEC is the most similar example of a large multinational coalition structure which resembles partial cooperation. Unlike OPEC however, the PNA deals with a renewable resource with variable endowment. Another example that shares some of the characteristics of the problem under examination is the cap and trade program related to greenhouse gases. Total emissions are decided together based on a process loosely resembling grandfathering and a certain amount of political considerations, and is then distributed to members which are sold as licenses. These licenses can be also considered to be global since they can be used anywhere.

The third contribution is with the idea of basing a revenue sharing mechanism on the average of an exogenous variable over time. Many of the prominent sharing mechanisms depend on complicated algorithms which are difficult to implement in the real world. The Shapley-value (Shapley 1953) calculates the average marginal contribution of each member. The nucleolus (Schmeidler 1969) rule attempts to maximizes the benefit of the least well off coalition. The Nash bargaining solution is egalitarian or equal-sharing in the sense that it values each player equally (Nash 1953). The proposed revenue sharing rule is simple and easy to understand, which does not deviate significantly from the current sharing mechanism which should improve its chances of being adopted.

The rest of the introduction provides an overview of the current literature. Section 5.2 introduces the model. Section 5.2.1 outlines the key results. Section 5.3 provides a discussion and the implications of the findings, and Section 5.4 concludes.

5.1.1 Literature Review

A considerable portion of the literature on coalitions in fisheries management has focused on non-cooperative games, which involve players reaching stable alliances through credible threats. In cooperative games players agree to certain terms which enable alliances to be formed. These games are enforced through punishment. Cooperative games can also include a transferable utility or sharing stage as part of the agreement, for example side payments. The PNA problem under consideration falls in to the category of cooperative games with transferable utility. Bailey, Rashid Sumaila, and Marko Lindroos (2010) surveys the use of game theory in fisheries economics, and M. Lindroos, V. Kaitala, and L. G. Kronbak (2007) provides a survey of coalition games in fisheries. Coalition games generally fall into either cooperative or non-cooperative games.

Coalition games in fisheries has its beginnings in two player games. Gordon R. Munro (1979) was one of the first to recognize the importance of game theory to the management of transboundary fisheries resources, with an analysis using two player games. After the ratification of the United Nations Convention on the Law of the Sea in 1982, Veijo Kaitala and Gordon R. Munro (1993) recognized the potential application of multi-player games to the management of straddling fisheries resources by more than two countries. Veijo Kaitala and G. Munro (1997) provided the first analysis of coalition games to the problem, by analyzing the Regional Fisheries Management Organizations (RFMO) that emerged from the United Nations Agreement on Highly Migratory Fish Stocks (cite UN) requiring multiple countries to work together to manage straddling fish stocks. They concluded that a significant issue with the new agreement was what they termed the new member problem. This is the situation where several countries cooperate and successfully raise the stock size of the joint resource. Subsequently other countries which were not part of the cooperation and made no contribution wish to join and reap the benefits. Another related issue is called the interloper problem, and refers to the policing of non-member fishing vessels who may attempt to free ride on the conservation efforts of the members. Veijo Kaitala and G. Munro (1997) suggested the introduction of transferable membership and a membership waiting period as possible solutions to the new member problem.

Many of the studies conducted on coalitions in the fisheries literature focused on two stage non-cooperative games, which are solved by backward induction. In the first stage coalitions are formed, and in the second stage countries and coalitions determine their best strategies. This approach yields Nash equilibrium which can then be analyzed to determine stability. Arnason, Magnusson, and Agnarsson (2000) and Marko Lindroos (2004a) applied a two stage game for the Norwegian spring spawning herring fishery. Anarson et. al. analyzed a five country game and concluded that the grand coalition is not stable unless side payments are allowed. The primary reason for this was that Norway which has the largest EEZ, requires substantial incentive to cooperate as it would be worse off relative to the alternative where it acts alone. Shapley values for each country were calculated and are presented as an option for the size of the side payments. Gordon R. Munro (1979) showed that side payments could be effective in overcoming the non-cooperative outcome that is typical in tragedy of the commons type of games. Lindroos and Kaitala showed that for a three player game, a full coalition approach is not feasible due to the high opportunity cost which is a result of the highly productive fishing fleets of the three countries. However, analysis with less productive fishing fleets allowed a full coalition to be more favorable. Pintassilgo (2003) extended these two stage coalition games to include externalities, and applied it to the Atlantic Bluefin tuna. He found that in the presence of strong externalities, a fair sharing rule is not sufficient to ensure the stability of the grand coalition.

An additional class of games includes a third state which involves the sharing of the surplus. These are called transferable utility (TU) games. Veijo Kaitala and Marko Lindroos (1998) examined the sharing of the surplus from the cooperation in the management of a straddling fish stock for a three player game. One player was a coastal state, and two were DWFN. They compared three sharing rules the Shapley-value (Shapley 1953), nucleolus (Schmeidler 1969), and the nash bargaining solution (Nash 1953). The Shapley value calculates the average marginal contribution of each member. The nucleolus rule attempts to maximizes the benefit of the least well off coalition. The Nash bargaining solution is egalitarian or equal-sharing in the sense that it values each player equally. Marko Lindroos (2004b) extended the same problem to two coastal states and two DWFN. The coastal states and DWFN are allowed to negotiate as a group and the results suggest that if costal states have efficient fleets, then they may be able to restrict the coalition negotiation of the DWFN by acting as a veto coalition.

Li (1998) suggested a fair sharing rule to improve the stability of a coalition. Possible rules which examined were nucleolus (Schmeidler 1969), Shapley-value (Shapley 1953), and egalitarian. Using a coalition game approach, Li found that a fair sharing rule would guarantee the stability of a coalition because inefficient members would be discouraged to enter as their share would be low. Pintassilgo and Duarte (2000) looked at the case of the northern blue-fin tuna, and showed that the transferable membership and the membership waiting period solutions are enough to prevent the breakdown of the coalition. The addition of new members to a coalition can have negative implications for the stability of the coalition (Hannesson 1997), however Marko Lindroos (2008) showed that new members may also have a stabilizing effect.

Lone Grønbæk Kronbak and Marko Lindroos (2006) analyzed a four stage game modeled after the Baltic sea cod fishery. In the first two stages authorities form coalitions, and then in the following two stages fishermen form coalitions. This study showed that the level of enforcement by authorities affects the coalition decisions of the fishermen.

Most of the studies mentioned above had stability as a primary concern. Yeeting et al. (2018) examined the case of the PNA fishery to determine the stability of the VDS under partial and full compliance. Her findings suggest that partial compliance results in improved stability relative to full compliance.

5.2 Model

To begin, the following simplifying assumptions are made. First, the share of fish in each time period t for each of the N countries can change. The distribution of this share of the stock of fish for each time period t is known, and the expected distribution over a total $T = \sum_{i=1}^{T} t_i$ periods is also known. Over some of the individual t periods, countries could have a high share of fish, and in others it could have a low share. Let α be a vector of the distribution of the stock of fish over all countries at each time period t (such that $\sum_{i=1}^{N} \alpha_i = 1$), and let β be a vector of the share of the average or expected stock of fish over the entire time period T, such that $\sum_{i=1}^{N} \beta_i = 1$. For simplicity I assume that for each year the total stock of fish over all of the countries does not change from year to year.

Under both full cooperation and partial cooperation, the authority or manager sets the total number of licenses over the entire time period L_T which is then split over the number of periods. Under full cooperation the coalition sells one license, and the revenue is split among the members based on the average share β over the T periods. Under partial cooperation, countries sell licenses individually after a total number of licenses has been set, and then split between each country as an average share β. Fishing vessels decide on which country to buy licenses from, and they have perfect information about the distribution of fish.

I assume that the demand function for licenses belongs in the following general class of functions.

$$w = p - pL^{\sigma}(\frac{c}{pqX})^{\sigma}$$

This particular functional form is based on the maximization problem of the fishing vessels under input regulation (See Appendix 5.A). p is the market price per ton of tuna, c is the cost of catching a ton of tuna, q is the catchability coefficient of a representative fishing vessel, and X is the stock of fish. σ is the coefficient which determines the convexity or concavity of the demand function. This general function can represent different demand conditions depending on the value of σ, which must be positive. For a linear demand function, $\sigma = 1$ which gives a simpler form as follows.

$$w = p - \frac{c}{qX}L$$

If $\sigma > 1$ then the demand function is concave, and when $\sigma < 1$ the demand function is convex. In all of these cases the intercepts remain the same which provides a convenient way to compare the revenue under different demand conditions. Figure 5.1 provides an illustration of the demand function with different values of σ.

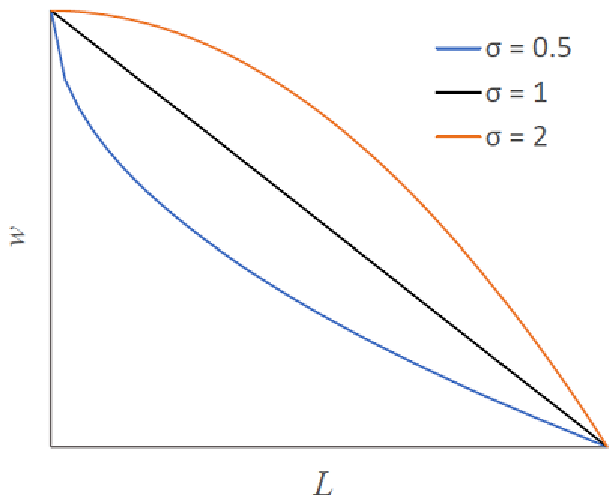


Figure 5.1: The general demand function with convex, linear and concave demand.

Note that the license price w increases with p, q and X, but decreases with c. This is an important feature of demand functions for fishing licenses, and although very simplified, reflects real world dynamics for fishing licenses. Since there is a single homogeneous fishing fleet buying licenses, I assume that p, c and q are constant across all of the countries. The only value that can be different is X. This allows for differing demand based on stock sizes.

5.2.1 Revenue Comparison

Single Period

Applying demand function for output regulation, the fishery managers maximization problem, which is the same for full and partial cooperation, and optimal L are as follows.

$$w = p - pL^{\sigma}(\frac{c}{pqX})^{\sigma}$$

$$\max_L \quad wL = (p - pL^\sigma (\frac{c}{pqX})^\sigma)L$$

$$L^* = \frac{pqX}{c(\sigma+1)^{\frac{1}{\sigma}}}$$

Substituting into the revenue function, revenue to each individual country from partial cooperation is

$$R^i_{PC} = (p - p(L^{i*}_{PC})^\sigma (\frac{c}{pqX^i})^\sigma)L^{i*}_{PC} = (p - p(\beta^i L^*_{PC})^\sigma (\frac{c}{pq\alpha^i X})^\sigma)\beta^i L^*_{PC}$$

$$R^i_{PC} = \Big[p - p\Big(\frac{\beta^i pqX}{c(\sigma+1)^{(\frac{1}{\sigma})}}\Big)^\sigma \Big(\frac{c}{pq\alpha^i X}\Big)^\sigma\Big]\frac{\beta^i pqX}{c(\sigma+1)^{(\frac{1}{\sigma})}}$$

$$R^i_{PC} = \beta^i \frac{p^2 qX_t}{c}\Big[\frac{1}{(\sigma+1)^{(\frac{1}{\sigma})}} - \Big(\frac{\beta^i}{\alpha^i}\Big)^\sigma \frac{1}{(\sigma+1)^{(\frac{1}{\sigma}+1)}}\Big] \tag{5.1}$$

For full cooperation, first I have to calculate total revenue to the coalition, which is then split as a share to the countries according to β^i.

$$R_{FC} = (p - p(L^*_{PC})^\sigma (\frac{c}{pqX})^\sigma)L^*$$

$$R_{FC} = \Big[p - p\Big(\frac{pqX}{c(\sigma+1)^{(\frac{1}{\sigma})}}\Big)^\sigma \Big(\frac{c}{pqX}\Big)^\sigma\Big]\frac{pqX}{c(\sigma+1)^{(\frac{1}{\sigma})}}$$

$$R_{FC} = \frac{p^2 qX_t}{c}\Big[\frac{1}{(\sigma+1)^{(\frac{1}{\sigma})}} - \frac{1}{(\sigma+1)^{(\frac{1}{\sigma}+1)}}\Big] \tag{5.2}$$

Revenue to each individual country under full cooperation is

$$R^i_{FC} = \beta^i \frac{p^2 qX_t}{c}\Big[\frac{1}{(\sigma+1)^{(\frac{1}{\sigma})}} - \frac{1}{(\sigma+1)^{(\frac{1}{\sigma}+1)}}\Big] \tag{5.3}$$

For brevity, let $\theta = (\sigma+1)^{(\frac{1}{\sigma})}$ and let $R_{FC} = \pi$ and $R_{PC} = \hat{\pi}$. The revenue functions from this point forward will be expressed as

$$\hat{\pi}_i = \beta^i \frac{p^2 qX_t}{c}\Big[\frac{1}{\theta} - \Big(\frac{\beta^i}{\alpha^i_t}\Big)^\sigma \frac{1}{\theta^{(1+\sigma)}}\Big] \tag{5.4}$$

$$\pi_i = \beta^i \frac{p^2 qX_t}{c}\Big[\frac{1}{\theta} - \frac{1}{\theta^{(1+\sigma)}}\Big] \tag{5.5}$$

Proposition 9. *If $T = 1$, the revenue to each country is identical under both full cooperation and partial cooperation.*

Proof. For $T = 1$, $\beta_i = \alpha_i$. It is clear that if $\frac{\beta_i}{\alpha_i} = 1$, then 5.4 is equal to 5.5. □

This result is important because it shows that there is no advantage to the full cooperation approach if it is implemented on a yearly basis.

Proposition 10. *If $T = 1$, the level of revenue in both partial and full cooperation has a positive relationship with the value of σ. That is, the more concave the demand curve the higher the revenue, and more convex the lower the revenue.*

Proof. Consider σ and the limits of θ and $\theta^{(1+\sigma)}$ as follows.

$$\lim_{\sigma\to\infty} \theta = 1$$

$$\lim_{\sigma\to 0} \theta = e \approx 2.7182$$

$$\lim_{\sigma\to\infty} \theta^{(1+\sigma)} = \infty$$

$$\lim_{\sigma\to 0} \theta^{(1+\sigma)} = e \approx 2.7182$$

As the demand function becomes more concave, θ approaches 1, and as it becomes more convex, θ approaches e. This implies that as the demand function becomes more concave, $\frac{1}{\theta}$ gets larger, and vice versa. Similarly, as the demand function becomes more concave, the limit for $\theta^{(1+\sigma)}$ is ∞, and as it becomes more convex the limit is equal to $e \approx 2.7182$. This implies that as the demand function becomes more concave, $\frac{1}{\theta^{(1+\sigma)}}$ gets smaller and vice versa. The result follows. □

By themselves these two results from a single period are fairly limited in what they can infer, but they do form a foundation for results for multiple periods in the next section. To see an illustration of these two results, let

$$\lambda^i_{FC} = \frac{1}{\theta} - \frac{1}{\theta^{(1+\sigma)}}$$

$$\lambda^i_{PC} = \frac{1}{\theta} - \left(\frac{\beta^i}{\alpha^i_t}\right)^{\sigma} \frac{1}{\theta^{(1+\sigma)}}$$

The second column in Table 5.2 shows the corresponding values for λ_{PC} and λ_{FC} given different values of σ. Note that $\lambda_{PC} = \lambda_{FC}$ since $\frac{\beta^i}{\alpha^i_t} = 1$ for $T = 1$. For illustration purposes I have included the third column in Table 5.2, showing how λ_{FC} is determined.

Table 5.2: Values for λ_{FC} and λ_{PC}, with varying σ

σ	λ_{FC}	λ_{PC}
0.25	$0.41 - 0.33 = 0.08$	$0.41 - \left(\frac{\beta^i}{\alpha^i}\right)^{0.25} 0.33$
0.5	$0.44 - 0.29 = 0.15$	$0.44 - \left(\frac{\beta^i}{\alpha^i}\right)^{0.5} 0.29$
1	$0.5 - 0.25 = 0.25$	$0.5 - \left(\frac{\beta^i}{\alpha^i}\right)^{1} 0.25$
2	$0.58 - 0.19 = 0.38$	$0.58 - \left(\frac{\beta^i}{\alpha^i}\right)^{2} 0.19$
4	$0.67 - 0.13 = 0.53$	$0.67 - \left(\frac{\beta^i}{\alpha^i}\right)^{4} 0.13$

Multiple Periods

The next step is to extend the model to multiple periods. Strictly speaking, all the variables can change from one period to the other. However for tractability, I will assume that the fishing fleets cost c, catchability q and the market price of fish p, all remain constant. Since β is the same over each time period, it does not change either. The critical variables that change will be the stock of fish X, and the share of fish α_i.

From 5.1 and 5.3, I sum over time periods $T > 1$ to get 5.7 and 5.6.

$$\hat{\pi}_i = \sum_{t=1}^{T} \beta^i \frac{p^2 q X_t}{c} \Big[\frac{1}{\theta} - \Big(\frac{\beta^i}{\alpha_t^i}\Big)^{\sigma} \frac{1}{\theta^{(1+\sigma)}}\Big] \tag{5.6}$$

$$\pi_i = \sum_{t=1}^{T} \beta^i \frac{p^2 q X_t}{c} \Big[\frac{1}{\theta} - \frac{1}{\theta^{(1+\sigma)}}\Big] \tag{5.7}$$

Now that α does not necessarily equal β, a comparison can be made between partial cooperation and full cooperation for a single period t, out of the total T periods. Since the only difference between λ_{PC} and λ_{FC}, is that λ_{PC} has an additional $\frac{\beta^i}{\alpha^i}$ term, these are the only terms necessary for comparison.

$$\lambda_{PC}^i = \frac{1}{\theta} - \Big(\frac{\beta^i}{\alpha_t^i}\Big)^{\sigma} \frac{1}{\theta^{(1+\sigma)}}$$

$$\lambda_{FC}^i = \frac{1}{\theta} - \frac{1}{\theta^{(1+\sigma)}}$$

For λ_{PC}, only positive values are of interest. Limiting the analysis to only positive values and holding θ constant, it follows that

$$0 \leq \lambda_{PC} \leq \frac{1}{\theta}$$

The corresponding limits for $\frac{\beta}{\alpha}$ from λ_{PC} are

$$\lambda_{PC} = 0, \quad \frac{\beta}{\alpha} = \theta$$
$$\lambda_{PC} = \frac{1}{\theta}, \quad \frac{\beta}{\alpha} = 0$$

The smaller is β_i relative to α_t^i, the larger is λ_{PC}. The maximum value that λ_{PC} can attain is $\frac{1}{\theta}$. The smallest value λ_{PC} can attain is 0, when $\frac{\beta}{\alpha} = \theta$. This implies that the range of possible values for $\frac{\beta}{\alpha}$ are $0 \leq \frac{\beta}{\alpha} \leq \theta$. These results are illustrated in Table 5.3. Table 5.4 shows numerical values for λ_{FC} and λ_{PC}, for values of σ equal to 0.5, 1, and 1.5 respectively.

Table 5.3: Maximum and minimum values for λ_{FC} and λ_{PC}, holding constant σ

	λ_{FC}	λ_{PC}
Max ($\frac{\beta}{\alpha} = 0$)	$\frac{1}{\theta} - \frac{1}{\theta^{(1+\sigma)}}$	$\frac{1}{\theta}$
$\frac{\beta}{\alpha} = 1$	$\frac{1}{\theta} - \frac{1}{\theta^{(1+\sigma)}}$	$\frac{1}{\theta} - \frac{1}{\theta^{(1+\sigma)}}$
Min ($\frac{\beta}{\alpha} = \theta$)	$\frac{1}{\theta} - \frac{1}{\theta^{(1+\sigma)}}$	0

These results show that for each individual country in each individual period t, revenue from partial cooperation varies with the share of the license β and the share of stock α, and can be less than or greater than revenue from full cooperation. This leads to two general propositions.

Proposition 11. *For each individual country in each individual period t, the smaller the share of the licenses β relative to the share of the total stock α, the larger is the revenue from partial cooperation relative to full cooperation, and vice versa.*

Table 5.4: Maximum and minimum values for λ_{FC} and λ_{PC}, for different values of σ and the corresponding θ

	λ_{FC}	λ_{PC}	$\lambda_{PC} - \lambda_{FC}$
$\sigma = 1.5,\ \ \theta = 1.8$ (concave demand)			
Max ($\frac{\beta}{\alpha} = 0$)	0.32	0.54	0.22
Min ($\frac{\beta}{\alpha} = \theta$)	0.32	0	-0.32
$\sigma = 1.5,\ \ \theta = 2$ (linear demand)			
Max ($\frac{\beta}{\alpha} = 0$)	0.25	0.5	0.25
Min ($\frac{\beta}{\alpha} = \theta$)	0.25	0	-0.25
$\sigma = 0.5,\ \ \theta = 2.25$ (convex demand)			
Max ($\frac{\beta}{\alpha} = 0$)	0.15	0.44	0.29
Min ($\frac{\beta}{\alpha} = \theta$)	0.15	0	-0.15

This result does not need a proof as it is straightforward. For each individual year, when $\alpha > \beta$, $\lambda_{PC} > \lambda_{FC}$, and when $\alpha < \beta$, $\lambda_{PC} < \lambda_{PC}$. Intuitively this makes sense because in a given year, if a country is receiving a share higher than average, then it would be better off selling licenses on it's own in that particular year. However, this implies that in other periods it will receive share lower than average, which means it would receive revenue lower than average. In this case of course it would be better off under full cooperation. Proposition 11 formally establishes that the income stream from partial cooperation will be more volatile relative to income from full cooperation. This is the first important result of this study.

Proposition 12. *For each individual country in each individual period t, the expected positive difference between revenue from partial cooperation and full cooperation increases with the convexity of the demand function and decreases with the concavity of the demand function.*

This result also does not need a proof as it is illustrated in Table 5.4, and follows from Proposition 10. To determine more specific results, I look at an application of the model to the simplest example possible which is a two-country two-period model.

Example: 2 Country, 2 Period Model
Let the subscripts denote the time period $t = \{1, 2\}$ and let the countries $N = \{A, B\}$ be denoted by the order (A, B) for α, β and π. α is stochastic, which determines β, the average of the α values over both time periods and the share of the licenses each country gets. β is constant over the two time periods.

$$\pi_i = \sum_{t=1}^{2} \beta^i \frac{p^2 q X_t}{c} \left[\frac{1}{\theta} - \frac{1}{\theta^{(1+\sigma)}}\right] = \beta^i \frac{p^2 q X_1}{c} \left[\frac{1}{\theta} - \frac{1}{\theta^{(1+\sigma)}}\right] + \beta^i \frac{p^2 q X_2}{c} \left[\frac{1}{\theta} - \frac{1}{\theta^{(1+\sigma)}}\right]$$

$$\pi_i = \left[\beta^i \frac{p^2 q}{c}\right] \left(X_1 \left[\frac{1}{\theta} - \frac{1}{\theta^{(1+\sigma)}}\right] + X_2 \left[\frac{1}{\theta} - \frac{1}{\theta^{(1+\sigma)}}\right]\right)$$

$$\pi_i = \left[\beta^i \frac{p^2 q}{c}\right] \left((X_1 + X_2)\frac{1}{\theta} - (X_1 + X_2)\frac{1}{\theta^{(1+\sigma)}}\right) \tag{5.8}$$

$$\hat{\pi} = \sum_{t=1}^{2} \beta^i \frac{p^2 q X_t}{c} \Big[\frac{1}{\theta} - \Big(\frac{\beta^i}{\alpha_t^i}\Big)^{\sigma} \frac{1}{\theta^{(1+\sigma)}}\Big] = \beta^i \frac{p^2 q X_1}{c} \Big[\frac{1}{\theta} - \Big(\frac{\beta^i}{\alpha_1^i}\Big)^{\sigma} \frac{1}{\theta^{(1+\sigma)}}\Big] + \beta^i \frac{p^2 q X_2}{c} \Big[\frac{1}{\theta} - \Big(\frac{\beta^i}{\alpha_2^i}\Big)^{\sigma} \frac{1}{\theta^{(1+\sigma)}}\Big]$$

$$\hat{\pi} = \Big[\beta^i \frac{p^2 q}{c}\Big] \Big(X_1 \Big[\frac{1}{\theta} - \Big(\frac{\beta^i}{\alpha_1^i}\Big)^{\sigma} \frac{1}{\theta^{(1+\sigma)}}\Big] + X_2 \Big[\frac{1}{\theta} - \Big(\frac{\beta^i}{\alpha_2^i}\Big)^{\sigma} \frac{1}{\theta^{(1+\sigma)}}\Big]\Big)$$

$$\hat{\pi} = \Big[\beta^i \frac{p^2 q}{c}\Big] \Big((X_1 + X_2)\frac{1}{\theta} - (\beta^i)^{\sigma} \Big[\frac{X_1}{(\alpha_1^i)^{\sigma}} + \frac{X_2}{(\alpha_2^i)^{\sigma}}\Big] \frac{1}{\theta^{(1+\sigma)}}\Big) \tag{5.9}$$

To compare the income over time, I examine 5.8 and 5.9.

$$\pi_i = \Big[\beta^i \frac{p^2 q}{c}\Big] \Big((X_1 + X_2)\frac{1}{\theta} - (X_1 + X_2) \frac{1}{\theta^{(1+\sigma)}}\Big)$$

$$\hat{\pi} = \Big[\beta^i \frac{p^2 q}{c}\Big] \Big((X_1 + X_2)\frac{1}{\theta} - (\beta^i)^{\sigma} \Big[\frac{X_1}{(\alpha_1^i)^{\sigma}} + \frac{X_2}{(\alpha_2^i)^{\sigma}}\Big] \frac{1}{\theta^{(1+\sigma)}}\Big)$$

The first thing to note is that the only difference between 5.8 and 5.9 are the very last terms. In particular the only terms required for comparison are

$$\mu_{FC} = X_1 + X_2 \qquad\qquad \mu_{PC} = (\beta^i)^{\sigma} \Big[\frac{X_1}{(\alpha_1^i)^{\sigma}} + \frac{X_2}{(\alpha_2^i)^{\sigma}}\Big]$$

The μ term that is smaller will yield a higher revenue since it is subtracted from the first term in the large brackets from 5.8 and 5.9. To compare, first I simplify μ_{PC} as follows.

$$\mu_{PC} = (\beta^i)^{\sigma} \Big[\frac{X_1}{(\alpha_1^i)^{\sigma}} + \frac{X_2}{(\alpha_2^i)^{\sigma}}\Big] = \Big(\frac{\sum_{t=1}^{T} \alpha_t}{T}\Big)^{\sigma} \Big[\frac{X_1}{(\alpha_1^i)^{\sigma}} + \frac{X_2}{(\alpha_2^i)^{\sigma}}\Big] = \Big(\frac{\alpha_1 + \alpha_2}{2}\Big)^{\sigma} \Big[\frac{X_1}{(\alpha_1^i)^{\sigma}} + \frac{X_2}{(\alpha_2^i)^{\sigma}}\Big]$$

$$\mu_{PC} = \Big(\frac{\alpha_1 + \alpha_2}{2\alpha_1^i}\Big)^{\sigma} X_1 + \Big(\frac{\alpha_1 + \alpha_2}{2\alpha_2^i}\Big)^{\sigma} X_2$$

Consider that $\sum_{i=1}^{T} X_t = X$. This means that if I let

$$x_t = \frac{X_t}{\sum_{i=1}^{T} X_t}$$

it implies that

$$\sum_{i=1}^{T} x_t = 1$$

This gives me 5.11, which are two simple convex combinations of α_t's.

$$x_1 + x_2 = \Big(\frac{\alpha_1 + \alpha_2}{2\alpha_1^i}\Big)^{\sigma} x_1 + \Big(\frac{\alpha_1 + \alpha_2}{2\alpha_2^i}\Big)^{\sigma} x_2 \tag{5.10}$$

While this condition depends on the value of σ, in general if either coefficient for x on the right hand side is greater than 1, then $\mu_{FC} < \mu_{PC}$. To see why consider a positive value y^{σ}. If $y > 1$

$$\lim_{\sigma \to 0} y^{\sigma} = y$$

$$\lim_{\sigma \to \infty} y^\sigma = \infty$$

If $y < 1$

$$\lim_{\sigma \to 0} y^\sigma = 1$$

$$\lim_{\sigma \to \infty} y^\sigma = 0$$

This means is that σ will not make any value greater than 1 if it is less than 1, and vice-versa. This implies that σ will not change which mechanism will yield a higher revenue level, although it may have bearing on the magnitude of the difference. So any results from the linear case where $\sigma = 1$, will generalize to either case.

Letting $\sigma = 1$ and simplifying 5.10 gives me 5.11. Extensions to three and four period versions can be found in appendix 5.E.

$$x_1\alpha_1\alpha_2 + x_2\alpha_1\alpha_2 = \alpha_2^2 x_1 + \alpha_1^2 x_2 \tag{5.11}$$

The general form of 5.11 is as follows.

$$(T-1)\Big(\sum_{t=1}^{T} x_t \Big(\prod_{t=1}^{T} \alpha_t\Big)\Big) = \sum_{t=1}^{T} x_t \Big(\sum_{s \neq t}^{T} (\alpha_s \prod_{s \neq t}^{T} \alpha_s)\Big) \tag{5.12}$$

Proposition 13. *If the stock levels remain constant from year to year, full cooperation always yields equal to or greater income than partial cooperation for each member country over $T > 1$ periods.*

Proof. When stock levels are equal over each time period, from 5.11, I get

$$\alpha_1\alpha_2 \leq \alpha_2^2 + \alpha_1^2$$

For multiple periods, from 5.12 I get

$$(T-1)\prod_{t=1}^{T} \alpha_t \leq \sum_{t=1}^{T} \alpha_t^2 \tag{5.13}$$

Since $0 \leq \alpha_t \leq 1$, this is always true. □

This result is that for all values of $0 \leq \alpha \leq 1$, if $X_1 = X_2$, it will always be true that full cooperation will yield higher revenues than partial revenue. The only time that the revenue from full cooperation and partial cooperation are equal is when $\alpha_1 = \alpha_2$.

Proposition 14. *If the stock levels vary considerably from year to year, it is possible that full cooperation may yield less income than partial cooperation for an individual member country over T periods.*

Proof. Rearranging 5.11 gives me 5.14, which is the condition that must be met if $\hat{\pi}_t > \pi_t$.

$$\frac{x_1}{x_2} > \frac{\alpha_1^2 - \alpha_1\alpha_2}{\alpha_1\alpha_2 - \alpha_2^2} \tag{5.14}$$

Let $\alpha_2 = \varepsilon\alpha_1$, and assume that $\alpha_1 > \alpha_2$ such that $0 \geq \varepsilon \geq 1$. Condition 5.14 then becomes

$$\frac{x_1}{x_2} > \frac{1-\varepsilon}{\varepsilon - \varepsilon^2} \tag{5.15}$$

Assuming that $x_1 > x_2$, the greater the difference between x_1 and x_2, the larger the left hand side of 5.15. The greater the difference between α_1 and α_2, larger the value of ε and the smaller the right hand side in 5.15. It is straightforward to show that under these conditions, $\hat{\pi}_t > \pi_t$. □

Proposition 14 will hold true if there is a significant difference between the total stock sizes in each period, with a corresponding large difference in the shares a country receives. The intuition behind these two results is as follows. If the fluctuations in the total stock of fish from year to year is minimal, then full cooperation will yield higher income. However, if there are significant fluctuations in the total fish stocks from year to year, then in certain cases where corresponding shares to a country vary considerably, partial cooperation may yield higher income levels. For example, let the year 1 total stock size be much larger than year 2, with country i enjoying a high share in year 1 and a low share in year 2. Under partial cooperation, it's income in year 1 would be very large, possibly large enough to offset the gain it will make from moving to full cooperation.

While such cases are possible, they are probably very rare in real world application of the PNA. Table 5.5 shows different combinations of x_1 and x_2 and the corresponding approximate values of ε where $\pi_t = \hat{\pi}_t$. The second row shows that for total stocks which decrease by around 33 percent, the difference in α from year 1 to year 2 such that revenue from partial cooperation is greater than that from full cooperation, must be greater than 66 percent. As the difference in stock levels from year 1 to year 2 increase, the threshold difference ε falls. The last row shows that for total stocks which decrease by around 88 percent, the difference in α such that revenue from partial cooperation is greater than that from full cooperation from year 1 to year 2, must be greater than 11 percent. It should be noted that for the stock size on the scale of the PNA, fluctuations of the magnitude shown in the table will be significant. One plausible scenario might occur if there was a significant decline of the fishery. These results imply then that it is highly unlikely that shares will vary enough such that countries observe revenue under partial cooperation exceed revenue from full cooperation. In any case, although country i may receive higher total revenue under such conditions, it will still have very large fluctuations in revenue from year to year.

Table 5.5: Stock level proportions and corresponding approximate values for ε where $\pi_t = \hat{\pi}_t$.

x_1	x_2	ε
0.6	0.4	0.66
0.7	0.3	0.43
0.8	0.2	0.25
0.9	0.1	0.11

5.2.2 Coalition Revenue

Next I examine total revenue for the coalition. The general equations are

$$\pi = \sum_{t=1}^{T} \sum_{i=1}^{N} \left[\beta^i \frac{p^2 q X_t}{c}\right] \left(\frac{1}{\theta} - \frac{1}{\theta^2}\right) \tag{5.16}$$

$$\hat{\pi} = \sum_{t=1}^{T}\sum_{i=1}^{N}\Big[\beta^i \frac{p^2 q X_t}{c}\Big]\Big(\frac{1}{\theta} - \frac{1}{\theta^{(1+\sigma)}}\Big(\frac{\beta^i}{\alpha_t^i}\Big)^{\sigma}\Big)$$

In a single period 2 country case, full cooperation gives me

$$\pi = \sum_{i=1}^{2}\beta_i \frac{p^2 q X_t}{c}\Big[\frac{1}{\theta} - \frac{1}{\theta^{(1+\sigma)}}\Big]$$

$$\pi = \beta_A \frac{p^2 q X_t}{c}\Big[\frac{1}{\theta} - \frac{1}{\theta^{(1+\sigma)}}\Big] + \beta_B \frac{p^2 q X_t}{c}\Big[\frac{1}{\theta} - \frac{1}{\theta^{(1+\sigma)}}\Big]$$

$$\pi = \frac{p^2 q X_t}{c}\frac{1}{\theta}(\beta_A + \beta_B) - \frac{p^2 q X_t}{c}\frac{1}{\theta^{(1+\sigma)}}(\beta_A + \beta_B) \tag{5.17}$$

Partial cooperation this gives me

$$\hat{\pi} = \sum_{i=1}^{N}\beta^i \frac{p^2 q X_t}{c}\Big[\frac{1}{\theta} - \frac{1}{\theta^{(1+\sigma)}}\Big(\frac{\beta^i}{\alpha^i}\Big)^{\sigma}\Big]$$

$$\hat{\pi} = \beta_A \frac{p^2 q X_t}{c}\Big[\frac{1}{\theta} - \frac{1}{\theta^{(1+\sigma)}}\Big(\frac{\beta_A}{\alpha_A}\Big)^{\sigma}\Big] + \beta_B \frac{p^2 q X_t}{c}\Big[\frac{1}{\theta} - \frac{1}{\theta^{(1+\sigma)}}\Big(\frac{\beta_B}{\alpha_B}\Big)^{\sigma}\Big]$$

$$\hat{\pi} = \frac{p^2 q X_t}{c}\frac{1}{\theta}(\beta_A + \beta_B) - \frac{p^2 q X_t}{c}\frac{1}{\theta^{(1+\sigma)}}\Big[\beta_A\Big(\frac{\beta_A}{\alpha_A}\Big)^{\sigma} + \beta_B\Big(\frac{\beta_B}{\alpha_B}\Big)^{\sigma}\Big] \tag{5.18}$$

Proposition 15. *For each individual period t, if the demand for licenses is linear or convex, then total income to the coalition from full cooperation will always be equal to or greater than total income from partial cooperation. If the demand for licenses is concave, then this result may not hold*

Proof. Comparing 5.17 and 5.18, for $\pi_t \geq \hat{\pi}_t$ to be true, the following condition must be satisfied.

$$1 \leq \sum_{i=1}^{N}\beta^i\Big(\frac{\beta^i}{\alpha_t^i}\Big)^{\sigma}$$

Let $N = \{A, B\}$. Applying to one of the periods in the 2 country 2 period case gives me

$$1 \leq \beta_A\Big(\frac{\beta_A}{\alpha_{At}}\Big)^{\sigma} + \beta_B\Big(\frac{\beta_B}{\alpha_{Bt}}\Big)^{\sigma} = \beta_A\Big(\frac{\beta_A}{\alpha_{At}}\Big)^{\sigma} + (1-\beta_A)\Big(\frac{1-\beta_A}{1-\alpha_{At}}\Big)^{\sigma} \tag{5.19}$$

Since they are shares, all the values of α and β must be within [0,1]. This means $(1-\beta_A)$ and $(1-\alpha_A)$ must also be within [0,1]. As long as these conditions are met it is straightforward to show that if the demand for licenses is linear ($\sigma = 1$) then

$$1 \leq \frac{\beta_A^2}{\alpha_A} + \frac{(1-\beta_A)^2}{1-\alpha_A}$$

If demand is convex, then this result also holds true because

$$\lim_{\sigma \to 0}\Big(\frac{\beta^i}{\alpha_t^i}\Big)^{\sigma} = 1$$

However, if demand is concave then at higher levels of σ this result may not hold because when $\frac{\beta^i}{\alpha_t^i} < 1$

$$\lim_{\sigma \to \infty} \left(\frac{\beta^i}{\alpha_t^i}\right)^\sigma = 0$$

$\square$

This result may appear suprising, because for the same mechanisms over a single year both input and output regulation yields the same revenue. However, the intuition behind this result is that when there is a mismatch in the share of licenses received and the share of fish in each country's waters, then not all licenses will be sold. This situation occurs when $\beta \neq \alpha$.

Total Periods

For total revenue over all of the periods, full cooperation gives me

$$\pi = \sum_{t=1}^{T} \sum_{i=1}^{N} \beta^i \frac{p^2 q X}{c} \Big[\frac{1}{\theta} - \frac{1}{\theta^{(1+\sigma)}}\Big]$$

Partial cooperation gives me

$$\hat{\pi} = \sum_{t=1}^{T} \sum_{i=1}^{N} \beta^i \frac{p^2 q X}{c} \Big[\frac{1}{\theta} - \frac{1}{\theta^{(1+\sigma)}} \Big(\frac{\beta^i}{\alpha^i}\Big)^\sigma\Big]$$

Applying to the two country two period case gives me

$$\pi = \frac{p^2 q}{c}\frac{1}{\theta}(\beta_A + \beta_B)[X_1 + X_2] - \frac{p^2 q}{c}\frac{1}{\theta^{(1+\sigma)}}\left(X_1\Big[\beta_A + \beta_B\Big] + X_2\Big[\beta_A + \beta_B\Big]\right) \tag{5.20}$$

$$\begin{aligned}\hat{\pi} = {} & \frac{p^2 q}{c}\frac{1}{\theta}(\beta_A + \beta_B)[X_1 + X_2] - \\ & \frac{p^2 q}{c}\frac{1}{\theta^{(1+\sigma)}}\left(X_1\Big[\beta_A\Big(\frac{\beta_A}{\alpha_1^A}\Big)^\sigma + \beta_B\Big(\frac{\beta_B}{\alpha_1^B}\Big)^\sigma\Big] + X_2\Big[\beta_A\Big(\frac{\beta_A}{\alpha_2^A}\Big)^\sigma + \beta_B\Big(\frac{\beta_B}{\alpha_2^B}\Big)^\sigma\Big]\right)\end{aligned} \tag{5.21}$$

Proposition 16. *Over the entire $T > 1$ periods, if the demand for licenses is linear or convex then total income to the coalition from full cooperation will always be greater than total income from partial cooperation. If the demand for licenses is concave, then this result may not hold.*

Proof. Comparing 5.20 and 5.21, for $\pi \geq \hat{\pi}$ to be true, the following condition must be satisfied.

$$\sum_{t=1}^{T} X_t \Big(\sum_{i=1}^{N} \beta^i\Big) \leq \sum_{t=1}^{T} X_t \Big(\sum_{i=1}^{N} \beta^i \Big[\frac{\beta^i}{\alpha_t^i}\Big]^\sigma\Big)$$

Let $N = \{A, B\}$. Applying to the 2 country 2 period case gives me

$$\begin{aligned} & X_1(\beta_A + \beta_B) + X_2(\beta_A + \beta_B) \leq \\ & \qquad X_1\Big[\beta_A\Big(\frac{\beta_A}{\alpha_{A1}}\Big)^\sigma + \beta_B\Big(\frac{\beta_B}{\alpha_{B1}}\Big)^\sigma\Big] + X_2\Big[\beta_A\Big(\frac{\beta_A}{\alpha_{A2}}\Big)^\sigma + \beta_B\Big(\frac{\beta_B}{\alpha_{B2}}\Big)^\sigma\Big]\end{aligned} \tag{5.22}$$

Once again the condition for 5.22 to be true is that for all individual periods t,

$$1 \le \beta_A\Big(\frac{\beta_A}{\alpha_{At}}\Big)^{\sigma} + \beta_B\Big(\frac{\beta_B}{\alpha_{Bt}}\Big)^{\sigma}$$

This is the same condition that was proved in 5.19 for proposition 15. It must follow that for linear and convex demand functions, $\pi \ge \hat{\pi}$. □

The general equations for total revenue are

$$\pi = \sum_{t=1}^{T}\sum_{i=1}^{N} \beta^i \frac{p^2 q X_t}{c}\Big[\frac{1}{\theta} - \Big(\frac{1}{\theta^{(1+\sigma)}}\Big)\Big] \tag{5.23}$$

$$\hat{\pi} = \sum_{t=1}^{T}\sum_{i=1}^{N} \beta^i \frac{p^2 q X_t}{c}\Big[\frac{1}{\theta} - \Big(\frac{\beta^i}{\alpha_t^i}\Big)^{\sigma} \frac{1}{\theta^{(1+\sigma)}}\Big] \tag{5.24}$$

Applying the model to the two country case gives me Table 5.6, which is the same as simple case in the introduction.For simplicity I have assumed that all of the constant are equal to 1 and that $\sigma = 1$. I have assumed that Country A is larger than country B. The table shows the total revenue over both periods from partial cooperation ($\hat{\pi}$) is lower relative to full cooperation (π).

Table 5.6: Illustration of profits for non-constant α. Assumes all constants are equal to 1 and $\sigma = 1$ for simplicity.

	β	α_1	α_2	$\hat{\pi}_1$	$\hat{\pi}_2$	π_1	π_2	$\hat{\pi} - \pi$
Country A	0.25	0.20	0.30	0.046	0.073	0.063	0.063	-0.005
Country B	0.75	0.80	0.70	0.199	0.174	0.187	0.187	-0.002

5.2.3 Preferences

From Proposition 13 and Proposition 14, it is not clear which management scheme each individual member country will prefer because those results depend on the stock of fish X from year to year. One way to make a comparison is to make general assumptions about a countries preferences and consider the income stream over T periods as lotteries. Lotteries are essentially a set of alternative outcomes, with associated probabilities for each outcome. In this case the outcomes are $\pi = R_{FC}$ and $\hat{\pi} = R_{PC}$.

More formally, let α be an S valued random variable ($S \in [0, 1]$), distributed according to some function $f(\alpha)$. Then π and $\hat{\pi}$ are functions mapping α to $\mathbb{R}$. For the full cooperation case, each country gets a share $\beta = \int \alpha f(\alpha) d\alpha$ of the total profit with probability 1. β is the same through each time period. For the partial cooperation case each country in each time period t gets a profit level π with probability $p(\alpha) = f(\alpha)d\alpha$. I assume that each country has rational preferences $\succsim$ defined over the outcomes π and $\hat{\pi}$ respectively. I assume this preference relation is complete and transitive, and satisfies the independence axiom. I make an additional assumption that from year to year, the distribution of α for a particular country does not change.

Since I consider α to be a random variable, from 5.6 I get the following.

$$\hat{\pi}_i = \Big[\beta^i \frac{p^2 q}{c}\Big]\Big(\frac{1}{\theta}\sum_{t=1}^{T} X_t - \Big(\frac{\beta^i}{\alpha_t^i}\Big)^{\sigma} \frac{1}{\theta^{(1+\sigma)}} \sum_{t=1}^{T} X_t\Big)$$

This means that any results from the single period case holds for multiple periods.

Proposition 17. *Assume α is distributed according to a symmetric distribution f(.) over the interval $[0,1]$, with a standard deviation $\sigma > 0$. Then, revenue from full cooperation at a given time t second-order stochastically dominates (SOSD) revenue from partial cooperation.*

Proof. The proof follows a version of the general definition of SOSD.

$$E[\pi] = \int_a^b \pi(\alpha) f(\alpha) d\alpha \quad \geq \quad \int_a^b \hat{\pi}(\alpha) f(\alpha) d\alpha = E[\hat{\pi}]$$

where $f(\alpha)$ is the probability distribution function of α. Since α is distributed symmetrically from $[0,1]$, this implies that α is distributed around some mean μ, which is

$$\mu = \int_0^1 \alpha f(\alpha) d\alpha = \beta$$

Substituting, the expected revenue under full cooperation is

$$E[\pi] = \int_0^1 \mu \frac{p^2 q X_t}{c}\Big(\frac{1}{\theta}\Big) f(\alpha) d\alpha - \int_0^1 \mu^2 \frac{p^2 q X_t}{c}\Big(\frac{1}{\theta^2}\Big) f(\alpha) d\alpha \tag{5.25}$$

Similarly, the expected revenue under partial cooperation is

$$E[\hat{\pi}] = \int_0^1 \mu \frac{p^2 q X_t}{c}\Big(\frac{1}{\theta}\Big) f(\alpha) d\alpha - \int_0^1 \mu\mu^{\sigma} \frac{p^2 q X_t}{c} \frac{1}{\alpha^{\sigma}}\Big(\frac{1}{\theta^2}\Big) f(\alpha) d\alpha \tag{5.26}$$

Once again the only difference are the right hand terms. The condition for $E[\pi] \geq E[\hat{\pi}]$ is that

$$\int_0^1 \mu \frac{p^2 q X_t}{c}\Big(\frac{1}{\theta^2}\Big) f(\alpha) d\alpha \leq \int_0^1 \mu^{\sigma} \frac{p^2 q X_t}{c} \frac{1}{\alpha^{\sigma}}\Big(\frac{1}{\theta^2}\Big) f(\alpha) d\alpha$$

$$\mu \int_0^1 f(\alpha) d\alpha \leq \mu^{\sigma} \int_0^1 \frac{1}{\alpha^{\sigma}} f(\alpha) d\alpha$$

The left hand side of the condition is

$$\mu \int_0^1 f(\alpha) d\alpha = \mu\Big[F(\alpha)\Big]_0^1 = \mu[F(1) - F(0)]$$

Similarly the right hand side is

$$\mu^{\sigma} \int_0^1 \frac{1}{\alpha} f(\alpha) d\alpha = \mu^{\sigma}\big[\frac{1}{\alpha}\int_0^1 f(\alpha) d\alpha - \int_0^1 \frac{-\sigma}{\alpha^{(\sigma+1)}}\Big(\int_0^1 f(\alpha) d\alpha\Big) d\alpha\big]$$

$$= \mu^{\sigma}\big[\frac{1}{\alpha}\big(F(1) - F(0)\big) + \int_0^1 \frac{1}{\alpha^{(\sigma+1)}}\big(F(1) - F(0)\big) d\alpha\big]$$

$$= \mu^{\sigma}\Big(\frac{1}{\alpha}\big(F(1) - F(0)\big) + \big(F(1) - F(0)\big)\Big[-\frac{1}{\alpha^{\sigma}}\Big]_0^1\Big)$$

Approximating $\varepsilon \approx 0$

$$= \mu^{\sigma}\Big(\frac{1}{\alpha}\big(F(1) - F(0)\big) + \big(F(1) - F(0)\big)\Big[-\Big(\frac{1}{1^{\sigma}} - \frac{1}{\varepsilon^{\sigma}}\Big)\Big]_0^1\Big)$$

Let

$$\eta = -1 + \frac{1}{\varepsilon^{\sigma}}$$

which is a large positive number. This finally gives me

$$\mu^{\sigma}\int_0^1 \frac{1}{\alpha} f(\alpha) d\alpha = \mu^{\sigma}\Big[\big(F(1) - F(0)\big)\big(\frac{1}{\alpha} + \eta\big)\Big]$$

Since $0 \leq \alpha \leq 1$, it follows that

$$\mu[F(1) - F(0)] \leq \mu^{\sigma}\Big[\big(F(1) - F(0)\big)\big(\frac{1}{\alpha} + \eta\big)\Big]$$

□

If I consider that countries have an utility function over revenue $u(\pi)$ with all of the usual assumptions, this result implies that countries who may be risk averse would prefer full cooperation to partial cooperation. This result is fairly general and can be applied to different distribution functions. I apply it to the uniform and normal distribution in Appendix 5.F.

5.3 Discussion

This study has four primary results. The first result is that the income stream is more volatile under partial cooperation. Although this is fairly intuitive from the example provided in the introduction, Proposition 11 formally establishes this result. Proposition 11 states that for each individual country in each individual period t, revenue from partial cooperation varies with the share of the license β and the share of stock α, and can be less than or greater than revenue from full cooperation. If $\alpha > \beta$ then the country would be better off under partial cooperation. However, this higher α has to be offset in other periods with lower α to average out to β. This ultimately leads to excess demand in some period and excess supply in others. If the share of fish stock for each country is constant over all time periods, partial cooperation will yield the same revenue as full cooperation. The intuition is that for the years where $\alpha < \beta$, a country will not be able to sell all of its licenses and so it will not have as much revenue as under full cooperation. For the years where $\alpha > \beta$, a country will have a shortage of licenses. Table 5.6 illustrates this.

Proposition 9 is also important for this first result, as it implies that full cooperation is only beneficial over multiple years. In other words, full cooperation has no benefits over partial cooperation if it is implemented yearly. Intuitively, this result makes sense because the premise behind full cooperation is averaging income over multiple years.

Proposition 13 and Proposition 14 together form the second main result in this study. If the total stock of fish to the coalition remains stable from year to year, revenue to each country is always greater under full cooperation. If total stock levels fluctuate significantly, it is possible that revenue to some countries could be higher under partial cooperation. Such significant fluctuations are rare in the real world, but can occur if for example there was a collapse of the fish stocks. Table 5.5 shows that stock levels need to vary considerably for partial cooperation to lead to higher revenue relative to full cooperation. These all point to this scenario being highly unlikely.

The third main result is derived mainly from Proposition 15 and Proposition 16. Together they find that total income to the coalition for each individual period for full cooperation will be equal to or greater than partial cooperation, only if the demand function is convex or linear. If the demand function is concave, this result may not hold. The convexity of the demand function for licenses plays an important role in the degree of the difference in the revenue between the two functions. For very concave demand functions, countries are better off under partial cooperation. The general form of the demand function adopted in this paper allows for representation of convex, linear and concave demand functions, while retaining the intercepts in all cases. The results show that the concavity or convexity of the demand function play an important role in determining the degree of difference between the two mechanisms. Proposition 10 says that under yearly implementation, the more concave the demand curve, the higher the revenue and vice versa. For multiple periods, Proposition 12 finds that the more convex the demand function, the greater the expected difference in revenue between full cooperation and partial cooperation, and vice versa.

The last major result of this study is that risk averse countries will prefer full cooperation to partial cooperation. I show in Proposition 17 that full cooperation second order stochastically dominates partial cooperation. This essentially implies that on average, income from full cooperation will be higher than partial coopertion. However, for some periods partial cooperation can have higher revenue. Table 5.4 shows how full cooperation yields a sure revenue level, but income from partial cooperation can be higher or lower. Countries which may be risk loving will prefer partial cooperation. Given that most governments have only a few years per term, it seems obvious that they will prefer to plan their budgets before time, such that they are not left with large income stream in their outgoing year. This implies that most governments would be risk averse. That debate however, is beyond the scope of this study.

In the model I assume that the stock of skipjack migrate between the waters of each of the countries in the PNA, and are therefore common to the majority of the coalition. For simplicity I assumed a single stock, and that each country has a share α of the stock in each time period. The total area encompassing the PNA is very large, and in some cases disjoint with pockets of international or high seas in between. However, when considering the entire stock as a whole, this makes no difference to the model since I have not relied on any inter-migration of fish.

One of the assumptions made in this study is that the demand functions for the coalition and each individual country have the same vertical intercept and the same slopes, which implies that each individual country has the same market power as the coalition. This assumption was made so that any benefits from the proposed approach are derived only from its design and not from market power gains. This assumption means that the revenue potential to the coalition and each individual country is the same under both approaches, which enables the comparison between the two approaches to be as objective as possible by disregarding any market power gains from the new approach. While this assumption may reflect the case for larger countries which have significantly larger shares relative to the smaller countries, it is unlikely that smaller countries can command enough market power to justify this assumption. It is probable that the market for the licenses resembles an oligopoly. In this case, then there will be some gains in revenue specifically from market power for the full cooperation approach relative to partial cooperation. For example if I assume that some countries have linear demand functions like that observed in perfectly competitive market, the proposed approach will yield large revenue levels relative to the current approach. This is an area for future research.

When examining coalitions, stability is usually an important consideration. The PNA has now been existence for more than two decades, and endured several deviations from the coalition rules by members. For this reason I assumed that the PNA is inherently stable focusing instead on showing that the revenue under full cooperation is at least as good as revenue under partial cooperation. One issue that is uncertain is how this proposed approach may affect the way that the shares are decided. Although the current approach is based primarily on grandfathering and fish stock shares, this process is not very clear and likely also entails some level of political considerations.

Policy Implications

This study has shown that full cooperation provides a consistent income stream relative to partial cooperation. The first policy question is whether these benefits are worth giving up control of fishing licenses and perhaps more importantly control over the amount of fishing in each EEZ. The primary benefit of full cooperation is the stable revenue stream. For countries with volatile stock shares, they will also experience an increase in revenue. Although it hasn't been shown in this study, the market power gains from full cooperation is likely to also be significant. Smaller countries who are more vulnerable to volatile stock shares because of their lower stock endowment may be the countries who can benefit the most from full cooperation. Larger countries on the other hand may not be as vulnerable to revenue fluctuations given their larger endowments. For them the benefits may not be as significant. The deciding point for political buy in for these larger countries is likely the degree of improvement of revenue from full cooperation.

The second policy consideration is how to implement full cooperation. Given the scale of the PNA and the fact that the two approaches are very similar, a gradual implementation scheme may be a prudent approach. Firstly, if the benefits are primarily to smaller countries, an initial step in implementation may be for smaller countries to sell a single license as a sub-coalition. This would give them greater market power relative to selling individually, while leaving the larger countries to continue with the local licensing. The coalition as a whole can be insulated from any unexpected issues which may arise. One possible problem with this is that forming a sub-coalition may cause stability issues within the PNA. Another possible intermediate step is to distribute the shares as licenses rather than revenue. This is technically equivalent to distributing revenue shares because the prices will be all the same. However, this would give countries control of their own finances and will not require the PNA to set up a central sale and finance facility.

One potential benefit from moving to full cooperation may be that it can serve as a catalyst for joint action on illegal fishng. Illegal fishing is a major problem not just for the PNA but for fishing in general. The PNA members countries EEZ are very large, and the members do not have sufficient resources to monitor and patrol their waters. As it currently stands, countries are essentially individually monitoring their own EEZ for illegal fishing with whatever little resources they have. With a joint selling facility, countries may find it easier to contribute to a regional fund to at least find a solution to the illegal fishing problem.

The final policy implication, at the very least this study should generate debate and perhaps encourage policy makers to examine why the current partial cooperation mechanism has inefficiencies. As it currently stands, some countries are not able to sell all of their licenses. These are the countries that will stand to benefit the most. This implies that either the predictions used to base the shares of licenses is incorrect, or the process used to determine the share is not based solely on the shares. This clearly implies that there must be space for improvement. This study could provide insight into methods on how to find and implement those improvements.

Limitations and Extensions

The main limitation with this study is the assumption that the endowment of stocks are known from year to year. This to some extent reflects how the PNA tentatively sets its TAC from year to year, and in that respect this limitation is also shared with partial cooperation. This tentative TAC implies that there is room to allow for uncertainty. This is important because if stock levels cannot be predicted with some level of accuracy, then full cooperation may not yield the expected benefits. A future study can extend this model to characterize the revenue streams under varying scenarios of uncertainty. This will be an important area for expansion in the future.

Some other assumptions that I make are that the cost of fishing are the same across all countries, and that the quality of the fish is the same through all countries. Since the area encompassing the PNA is very large, this is not likely to be the case. However the model can easily allow for expansion in this area in the future

One simple extension of this study will be to include market power gains. This is simple and only requires minor modification of the demand function. This particular area of future work would be very useful if data could be used to estimate the extent of market power for each country.

5.4 Conclusion

In this paper I analyze two approaches to revenue sharing in the PNA. The first is partial cooperation, and is the current arrangement where the number of total licenses is set together then distributed to members to sell individually. The second is a full cooperation approach where the total number of licenses are set and sold together as one entity. Under partial cooperation, the licenses are distributed individually according to some sharing mechanism based on the historical catch as well as the stock levels available to each country. Under the proposed arrangement for full cooperation, the licenses are set and sold together and the revenue is shared among members according to same sharing rule used in partial cooperation.

This study has four primary results. The first result is that the income stream from full cooperation will be more stable than income from partial cooperation. The second result is that if the total stock of fish to the coalition remains stable from year to year, revenue to each country is always greater under full cooperation. If total stock levels fluctuate significantly, it is possible that revenue to some countries could be higher under partial cooperation. This can occur if for example there was a collapse of the fish stocks. The third result is that total income to the coalition for each individual period for full cooperation will be equal to or greater than partial cooperation only if the demand function is convex or linear. If the demand function is concave, this result may not hold. For very concave demand functions, countries are better off under partial cooperation.

The last major result of this study is that risk averse countries will prefer full cooperation to partial cooperation, while countries which may be risk loving will prefer partial cooperation.

Smaller countries who are more vulnerable to volatile stock shares because of their lower stock endowment will be the countries who can benefit the most from full cooperation. Larger countries on the other hand may not be as vulnerable to revenue fluctuations given their larger endowments. For them the benefits may not be as significant. The deciding point for political buy in for these larger countries is likely the degree of improvement of revenue from full cooperation.

Given the scale of the PNA and the fact that the two approaches are very similar, a gradual implementation scheme may be a prudent approach. Firstly, if the benefits are primarily to smaller countries, an initial step in implementation may be for smaller countries to sell a single license as a sub-coalition. Another possible intermediate step is to distribute the shares as licenses rather than revenue. This is technically equivalent to distributing revenue shares,but would give countries control of their own finances and will not require the PNA to set up a central sale and finance facility. One potential benefit from moving to full cooperation may be that it can serve as a catalyst for joint action on illegal fishing. With a joint selling facility, countries may find it easier to contribute to a regional fund to at least find a solution to the illegal fishing problem.

The main limitation with this study is the assumption that the endowment of stocks are known from year to year. Although I do not include uncertainty in this model this will be an important area for expansion of the model. Other assumptions that I make are that the cost of fishing are the same across all countries, and that the quality of the fish is the same through all countries. The model can be relaxed to allow for expansion in this respect in the future. Another simple extension of this study will be to include market power gains to fully characterize the gains under full cooperation.

Appendix 3

5.A Demand Functions

Under both of these cases, p is the market price per ton of tuna, c is the cost of catching a ton of tuna, q is the catchability coefficient of a representative fishing vessel, and X is the stock of fish. Note that in both cases, the license price w increases with p, q and X, but decreases with c.

5.A.1 Input Regulation

The profit function of the fishing vessel under input regulation is

$$\pi_k = pqXe - we - ce$$

Taking the first order condition gives me

$$\max_e pqXe - we - ce$$

$$pqx - w - c = 0$$

which finally gives me the demand function of each individual fishing vessel

$$w = pqX - c$$

5.A.2 Output Regulation

The profit function of the fishing vessel under output regulation is

$$\pi_k = pqXe - wqXe - ce$$

Taking the first order condition gives me

$$\max_e pqXe - wqXe - ce$$

$$pqx - wqx - c = 0$$

which finally gives me the demand function of each individual fishing vessel

$$w = p - \frac{c}{qX}$$

5.A.3 Market Demand

In order to represent a wider spectrum of cases, consider the following class of general demand functions which can be used represent linear, convex and concave demand functions. y is the dependent variable and x is the independent variable, a and b are constants. When $0 < \sigma < 1$ the demand is convex. When $\sigma = 1$, the demand is linear. Finally when $\sigma > 1$ the demand is concave.

$$y = a - ax^{\sigma}\left(\frac{b}{a}\right)^{\sigma}$$

$$y = a - \frac{b}{a}x$$

The individual vessel demand functions in 5.A.1 and 5.A.2 have desirable characteristics. The license price w increases with p, q and X, but decreases with c. To get market demand functions based on 5.A.1 and 5.A.2, substitute in w as the dependent variable and L as the independent variable. Substitutions for a and b depend on whether it is input and output regulation.

For input regulation, substitute $a = pqX$ and $b = c$. The general and linear cases are as follows

$$w = pqX - pqXL^{\sigma}\left(\frac{c}{pqX}\right)^{\sigma}$$

$$w = pqX - cL$$

For output regulation, substitute $a = p$ and $b = \frac{c}{qX}$. The general and linear cases are as follows

$$w = p - pL^{\sigma}\left(\frac{c}{pqX}\right)^{\sigma}$$

$$w = p - \frac{c}{qX}L$$

5.B Optimal Licenses

Optimal licenses isthe same under both input and output regulation. In this paper I have used output regulation, however the results are the same.

5.B.1 Output Regulation

Under output regulation, the demand function and optimal L are as follows.

$$w = p - pL^{\sigma}(\frac{c}{pqX})^{\sigma}$$

$$\max_{L} \Big(pL - pL^{\sigma+1}(\frac{c}{pqX^{i}})^{\sigma}\Big)$$

First order condition is

$$p - p(\sigma+1)L^{\sigma}(\frac{c}{pqX^{i}})^{\sigma} = 0$$

$$p = pL^{\sigma}(\frac{c}{pqX})^{\sigma}$$

$$L^{\sigma} = (\frac{pqX}{c})^{\sigma}$$

Optimal license numbers are

$$L^{*} = \frac{pqX}{c(\sigma+1)^{\frac{1}{\sigma}}}$$

5.B.2 Input Regulation

Under input regulation, the demand function and optimal L are as follows .

$$w = pqX - pqXL^{\sigma}(\frac{c}{pqX})^{\sigma}$$

$$\max_{L} \Big(pqXL - pqXL^{\sigma+1}(\frac{c}{pqX})^{\sigma}\Big)$$

First order condition is

$$pqX - pqX(\sigma+1)L^{\sigma}(\frac{c}{pqX})^{\sigma} = 0$$

$$pqX = pqX(\sigma+1)L^{\sigma}(\frac{c}{pqX})^{\sigma}$$

$$L^{\sigma} = \frac{1}{(\sigma+1)}(\frac{pqX}{c})^{\sigma}$$

Optimal license numbers are

$$L^{*} = \frac{pqX}{c(\sigma+1)^{\frac{1}{\sigma}}}$$

5.C Partial Cooperation Revenue

The revenue for each country under partial cooperation is

$$R^i_{PC} = (pqX - pqX(L^{i*}_{PC})^\sigma(\frac{c}{pqX^i})^\sigma)L^{i*}_{PC} = (pqX - pqX(\beta^i L^*_{PC})^\sigma(\frac{c}{pq\alpha^i X})^\sigma)\beta^i L^*_{PC}$$

$$R^i_{PC} = \Big[pqX - pqX\Big(\frac{\beta^i pqX}{c(\sigma+1)^{(\frac{1}{\sigma})}}\Big)^\sigma\Big(\frac{c}{pq\alpha^i X}\Big)^\sigma\Big]\frac{\beta^i pqX}{c(\sigma+1)^{(\frac{1}{\sigma})}}$$

$$R^i_{PC} = \Big[pqX - pqX\Big(\frac{\beta^i}{(\sigma+1)^{(\frac{1}{\sigma})}}\Big)^\sigma\Big(\frac{1}{\alpha^i}\Big)^\sigma\Big]\frac{\beta^i pqX}{c(\sigma+1)^{(\frac{1}{\sigma})}}$$

$$R^i_{PC} = \beta^i\frac{(pqX)^2}{c}\Big[\frac{1}{(\sigma+1)^{(\frac{1}{\sigma})}} - \Big(\frac{\beta^i}{\alpha^i}\Big)^\sigma\frac{1}{(\sigma+1)^{(\frac{1}{\sigma}+1)}}\Big]$$

5.D Full Cooperation Revenue

The revenue for each country under full cooperation is

$$R^i_{FC} = (pqX - pqX(L^*_{PC})^\sigma(\frac{c}{pqX})^\sigma)L^*_{PC}$$

$$R^i_{FC} = \Big[pqX - pqX\Big(\frac{pqX}{c(\sigma+1)^{(\frac{1}{\sigma})}}\Big)^\sigma\Big(\frac{c}{pqX}\Big)^\sigma\Big]\frac{pqX}{c(\sigma+1)^{(\frac{1}{\sigma})}}$$

$$R^i_{FC} = \beta^i\frac{(pqX)^2}{c}\Big[\frac{1}{(\sigma+1)^{(\frac{1}{\sigma})}} - \frac{1}{(\sigma+1)^{(\frac{1}{\sigma}+1)}}\Big]$$

$$R^i_{FC} = \beta^i\frac{p^2qX_t}{c}\Big[\frac{1}{(\sigma+1)^{(\frac{1}{\sigma})}} - \frac{1}{(\sigma+1)^{(\frac{1}{\sigma}+1)}}\Big] \tag{5.27}$$

5.E Revenue Comparison

$$\mu_{PC} = \frac{X_1 + X_2 + X_3}{3} + \frac{X_1(\alpha_2^2\alpha_3 + \alpha_2\alpha_3^2) + X_2(\alpha_1^2\alpha_3 + \alpha_1\alpha_3^2) + X_3(\alpha_1^2\alpha_2 + \alpha_1\alpha_2^2)}{3\alpha_1\alpha_2\alpha_3}$$

$$\mu_{FC} = \mu_{PC}$$

$$X_1+X_2+X_3 = \frac{X_1 + X_2 + X_3}{3} + \frac{X_1(\alpha_2^2\alpha_3 + \alpha_2\alpha_3^2) + X_2(\alpha_1^2\alpha_3 + \alpha_1\alpha_3^2) + X_3(\alpha_1^2\alpha_2 + \alpha_1\alpha_2^2)}{3\alpha_1\alpha_2\alpha_3}$$

$$\frac{2}{3}(X_1 + X_2 + X_3) = \frac{X_1(\alpha_2^2\alpha_3 + \alpha_2\alpha_3^2) + X_2(\alpha_1^2\alpha_3 + \alpha_1\alpha_3^2) + X_3(\alpha_1^2\alpha_2 + \alpha_1\alpha_2^2)}{3\alpha_1\alpha_2\alpha_3}$$

$$2(X_1 + X_2 + X_3) = \frac{X_1(\alpha_2^2\alpha_3 + \alpha_2\alpha_3^2) + X_2(\alpha_1^2\alpha_3 + \alpha_1\alpha_3^2) + X_3(\alpha_1^2\alpha_2 + \alpha_1\alpha_2^2)}{\alpha_1\alpha_2\alpha_3}$$

$$2\alpha_1\alpha_2\alpha_3(X_1 + X_2 + X_3) = X_1(\alpha_2^2\alpha_3 + \alpha_2\alpha_3^2) + X_2(\alpha_1^2\alpha_3 + \alpha_1\alpha_3^2) + X_3(\alpha_1^2\alpha_2 + \alpha_1\alpha_2^2)$$

$$\mu_{PC} = \frac{X_1 + X_2 + X_3 + X_4}{4} + \frac{X_1(\alpha_2^2\alpha_3\alpha_4 + \alpha_2\alpha_3^2\alpha_4 + \alpha_2\alpha_3\alpha_4^2) + X_2(\alpha_1^2\alpha_3\alpha_4 + \alpha_1\alpha_3^2\alpha_4 + \alpha_1\alpha_3\alpha_4^2)}{4\alpha_1\alpha_2\alpha_3\alpha_4} + \frac{X_3(\alpha_1^2\alpha_2\alpha_4 + \alpha_1\alpha_2^2\alpha_4 + \alpha_1\alpha_2\alpha_4^2) + X_4(\alpha_1^2\alpha_2\alpha_3 + \alpha_1\alpha_2^2\alpha_3 + \alpha_1\alpha_2\alpha_3^2)}{4\alpha_1\alpha_2\alpha_3\alpha_4}$$

$$\mu_{FC} = \mu_{PC}$$

$$3\alpha_1\alpha_2\alpha_3\alpha_4(X_1+X_2+X_3+X_4) = X_1(\alpha_2^2\alpha_3\alpha_4+\alpha_2\alpha_3^2\alpha_4+\alpha_2\alpha_3\alpha_4^2)+X_2(\alpha_1^2\alpha_3\alpha_4+\alpha_1\alpha_3^2\alpha_4+\alpha_1\alpha_3\alpha_4^2)+ X_3(\alpha_1^2\alpha_2\alpha_4 + \alpha_1\alpha_2^2\alpha_4 + \alpha_1\alpha_2\alpha_4^2) + X_4(\alpha_1^2\alpha_2\alpha_3 + \alpha_1\alpha_2^2\alpha_3 + \alpha_1\alpha_2\alpha_3^2)$$

5.F Distributions

Proposition 18. *Assume $\alpha \sim U[a,b]$. Revenue from full cooperation first-order stochastically dominates (FOSD) revenue from partial cooperation. That is, member countries always prefer full cooperation to partial cooperation.*

Proof. The proof follows a general definition of FOSD,

$$E[\pi] = \int_a^b \pi(\alpha) f(\alpha) d\alpha \quad \geq \quad \int_a^b \hat{\pi}(\alpha) f(\alpha) d\alpha = E[\hat{\pi}]$$

where $f(\alpha)$ is the probability distribution function of α. Let $R^i_{FC} = \pi^i$ (5.7), and $R^i_{PC} = \hat{\pi}^i$ (5.6). Since α is a share of the stock fish in each country, assume that α is distributed uniformly from $a = 0$ to $b = 1$. This means that

$$f(\alpha) = \frac{1}{b-a} = 1$$

$$\int_0^1 f(\alpha) d\alpha = \Big[\frac{1}{b-a}\Big]_0^1 = 1$$

$$\beta = \int_0^1 \alpha f(\alpha) d\alpha = \int_0^1 \frac{\alpha}{b-a} d\alpha = \Big[\frac{\alpha^2}{2}\Big]_0^1 = \frac{1}{2}$$

The expected revenue under full cooperation is

$$E[\pi] = \int_0^1 \Big(\int_0^1 \alpha f(\alpha) d\alpha \Big) \frac{p^2 q X_t}{c} \Big[\frac{1}{\theta} - \frac{1}{\theta^2}\Big] f(\alpha) d\alpha$$

$$E[\pi] = \frac{p^2 q X_t}{2c} \Big[\frac{1}{\theta} - \frac{1}{\theta^2}\Big]$$

$$E[\pi] = \frac{p^2 q X_t}{2c} \Big(\frac{1}{\theta}\Big) - \frac{p^2 q X_t}{2c} \Big(\frac{1}{\theta^2}\Big) \tag{5.28}$$

The expected revenue under partial cooperation is

$$E[\hat{\pi}] = \int_0^1 \Big(\int_0^1 \alpha f(\alpha) d\alpha \Big) \frac{p^2 q X_t}{c} \Big[\frac{1}{\theta} - \Big(\int_0^1 \alpha f(\alpha) d\alpha \Big) \frac{1}{\alpha} \frac{1}{\theta^2}\Big] f(\alpha) d\alpha$$

$$= \int_0^1 \frac{p^2 q X_t}{2c} \Big(\frac{1}{\theta}\Big) d\alpha - \int_0^1 \frac{p^2 q X_t}{4c} \frac{1}{\alpha} \Big(\frac{1}{\theta^2}\Big) d\alpha$$

The problem here is that the relationship $\int \frac{1}{x} dx = \log(x)$ does not hold for non-positive bounds. To get around this, I approximate the second term as follows. Let ε be a very small but positive number close to zero. Then

$$\int_\varepsilon^1 \frac{p^2 q X_t}{4c} \frac{1}{\alpha} \Big(\frac{1}{\theta^2}\Big) d\alpha = \frac{p^2 q X_t}{4c} \Big(\frac{1}{\theta^2}\Big) (-\log(\varepsilon))$$

$\log(\varepsilon)$ yields a large negative number. Therefore, $-\log(\varepsilon)$ yields a large positive number, which I denote as η.

$$E[\hat{\pi}] = \frac{p^2 q X_t}{2c} \Big(\frac{1}{\theta}\Big) - \frac{\eta p^2 q X_t}{4c} \Big(\frac{1}{\theta^2}\Big) \tag{5.29}$$

From 5.28 and 5.29, it then must be true that $E[\pi] > E[\hat{\pi}]$. $\square$

Proposition 19. *Assume $\alpha \sim N(\mu, \sigma^2)$. Revenue from full cooperation first-order stochastically dominates (FOSD) revenue from partial cooperation.*

Proof. The proof follows the same steps as in Proposition 18.

$$E[\pi] = \int_0^1 \pi(\alpha) f(\alpha) d\alpha = pi(\alpha) \int_0^1 f(\alpha) d\alpha - \int_0^1 \pi'(\alpha) \big(\int_0^1 f(\alpha) d\alpha \big) d\alpha$$

$$f(\alpha) = \frac{e^{\frac{-(x-\mu)^2}{2\sigma^2}}}{\sqrt{2\pi}\sigma} \qquad\qquad \pi'(\alpha) = 0$$

$$\int_0^1 f(\alpha) d\alpha = \int_0^1 \frac{e^{\frac{-(x-\mu)^2}{2\sigma^2}}}{\sqrt{2\pi}\sigma} d\alpha = 1.erf \frac{0.353553}{\sigma}$$

$$\beta = \int_0^1 \alpha f(\alpha) d\alpha = \int_0^1 \alpha \frac{e^{\frac{-(x-\mu)^2}{2\sigma^2}}}{\sqrt{2\pi}\sigma} d\alpha = \frac{1}{2} erf \frac{0.353553}{\sigma}$$

Let $\alpha \sim N(\mu, \sigma^2)$.

$$E[\pi] = \Big(\int_0^1 \alpha f(\alpha) d\alpha \Big) \frac{p^2 q X_t}{c} \Big[\frac{1}{\theta} - \frac{1}{\theta^2} \Big] \int_0^1 f(\alpha) d\alpha$$

$$E[\pi] = \frac{p^2 q X_t}{2c} \Big[\frac{1}{\theta} - \frac{1}{\theta^2} \Big]$$

$$E[\pi] = \frac{p^2 q X_t}{2c} \Big[\frac{1}{\theta} \Big] - \frac{p^2 q X_t}{2c} \Big[\frac{1}{\theta^2} \Big] \tag{5.30}$$

$$E[\hat{\pi}] = \int_0^1 \hat{\pi}(\alpha) f(\alpha) d\alpha = \hat{\pi}(\alpha) \int_0^1 f(\alpha) d\alpha - \int_0^1 \hat{\pi}'(\alpha) \big(\int_0^1 f(\alpha) d\alpha \big) d\alpha$$

$$E[\hat{\pi}] = \beta^i \frac{p^2 q X_t}{c} \Big[\frac{1}{\theta} - \frac{\beta}{\alpha} \frac{1}{\theta^2} \Big] \int_0^1 f(\alpha) d\alpha - \int_0^1 \beta \frac{p^2 q X_t}{c} \Big[\frac{\beta}{\alpha^2} \frac{1}{\theta^2} \Big] \big(\int_0^1 f(\alpha) d\alpha \big) d\alpha$$

$$\begin{aligned} E[\hat{\pi}] = \Big(\int_0^1 \alpha f(\alpha) d\alpha \Big) \frac{p^2 q X_t}{c} \Big[\frac{1}{\theta} - \Big(\int_0^1 \alpha f(\alpha) d\alpha \Big) \frac{1}{\alpha} \frac{1}{\theta^2} \Big] \int_0^1 f(\alpha) d\alpha \\ - \int_0^1 \frac{p^2 q X_t}{c} \Big[\Big(\int_0^1 \alpha f(\alpha) d\alpha \Big)^2 \frac{1}{\alpha^2} \frac{1}{\theta^2} \Big] \big(\int_0^1 f(\alpha) d\alpha \big) d\alpha \end{aligned}$$

$$E[\hat{\pi}] = \frac{p^2 q X_t}{2c} \Big[\frac{1}{\theta} - \frac{1}{2\alpha} \frac{1}{\theta^2} \Big] - \int_0^1 \frac{p^2 q X_t}{4c} \Big[\frac{1}{\alpha^2} \frac{1}{\theta^2} \Big] d\alpha$$

Let

$$\int_\varepsilon^1 \frac{p^2 q X_t}{4c} \Big[\frac{1}{\alpha^2} \frac{1}{\theta^2} \Big] d\alpha \approx \int_0^1 \frac{p^2 q X_t}{4c} \Big[\frac{1}{\alpha^2} \frac{1}{\theta^2} \Big] d\alpha$$

$$E[\hat{\pi}] = \frac{p^2 q X_t}{2c} \Big[\frac{1}{\theta} - \frac{1}{2\alpha} \frac{1}{\theta^2} \Big] - \Big[\frac{p^2 q X_t}{4c} \Big[\frac{\log(\alpha)}{\theta^2} \Big] \Big]_\varepsilon^1$$

$$E[\hat{\pi}] = \frac{p^2 q X_t}{2c}\left[\frac{1}{\theta}\right] - \frac{p^2 q X_t}{4c}\left[\frac{1}{\alpha\theta^2}\right] - \frac{p^2 q X_t}{4c}\left[\frac{\eta}{\theta^2}\right]$$

$$E[\hat{\pi}] = \frac{p^2 q X_t}{2c}\left[\frac{1}{\theta}\right] - \frac{p^2 q X_t}{4c}\frac{1}{\theta^2}\left[\frac{1}{\alpha} + \eta\right] \quad (5.31)$$

From 5.30 and 5.31 it must be true that $E[\pi] > E[\hat{\pi}]$. $\square$

Chapter 6

Policy Implications

Chapter 3 developed the heterogeneous model for a single country. The most significant result of the heterogeneous model for a single country is that the revenues under input and output regulation schemes are not equal. The analysis finds that output regulation will generate higher revenues relative to input regulation. These results strongly suggest that for a single country, an output regulation management scheme is recommended. Although this result has important implications for resource management in general, it has limited specific policy implications for the PNA case with a coalition of seven countries.

Applying the model to a more PNA relevant two-country setting in Chapter 4 finds that although output regulation yields higher revenue to countries, the harvest tagets for output regulation may not be reached. This implies that under the assumptions made in this study, output regulation may not be supportable. One key assumption is the constant cost of fishing over different countries. If the costs of fishing over different member countries is the same, then the PNA may be better off retaining the VDS. However, if the cost of fishing over different countries are significantly different, then output based quota regulation could be supportable. In this case a switch to output regulation would be recommended given the higher revenue levels that are possible.

A serious issue for the PNA is the prevalence of illegal and unreported fishing (IUU). The Pacific countries are actively working to improve monitoring and surveillance, however the Forum Fisheries Agency (FFA 2016b) report suggests that the majority of IUU activities in the Pacific are by fishing vessels that are licensed to operate in the Pacific region. This has important implications for the VDS as this suggests that stronger measures are required to improve monitoring of fishing vessels and their catch levels. If fishing vessels can continue to fish illegally or under report catch sizes, then a switch to harvest based licenses will not be successful. On the other hand if appropriate monitoring measures are taken, a switch to output regulation would impact rent for fishing vessels negatively. This may increase the incentives to fish illegally instead of buying licenses. In this case monitoring becomes even more important. Countries may consider setting aside revenues from licenses to combat IUU fishing.

One implication from Chapter 4 is that the PNA should set modest harvest targets, and consider a safety margin for the number of licenses that it sells. The analysis suggest that the conditions required for the a fishery manager to hit the exact harvest targets are very specific, and hence unlikely to occur. This implies that it is more likely that the harvest targets set by the PNA are either not met, or they are exceeded. Furthermore, the analysis suggests that this experience is likely to be different for each of the countries. This reflects the real world experience for some PNA countries that are unable to sell all of their licenses, while other have excess demand for their licenses and therefore have incentive to sell more licenses than they are allocated. This experience suggests the PNA should examine current licenses sales arrangements and pricing mechanisms to see if improvements can be made to ensure that at all licenses can be sold. Although licenses can be traded among countries, this does not adress the underlying cause of this demand discrepancy.

The PNA is a coalition of eight countries, and so a theoretical analysis based on the methodology outlined in this study will be very complicated. In addition to this, licenses are sold using auctions which are complex and notoriously difficult to correctly implement. One approach may be to apply empirical licenses sales data to examine fishing vessels incentives within the theoretical framework provided in this study, to examine if pricing mechanisms can be modified to improve license sales.

Together the results from Chapter 3 and 4 suggests that selling a single licenses giving vessels access to all countries would greatly simplify the management of the fishery and yield higher income levels. However, these models are not ideal for examining this issue because they do not consider the mechanism used to share the revenue, as well as the stability of the revenue stream over time. In Chapter 5, I compare the returns from selling a single global license relative to individual local licenses by developing a revenue sharing mechanism that can incorporate both approaches. The result show that a single license yields not only yields greater revenue levels, but also a more stable revenue stream over time.

One of the key benefits of individual licenses specific to each country is that each country retains control of fishing license sales. Not only does this insulate revenue streams between members but more importantly it gives countries control over the amount of fishing conducted in each EEZ. The primary benefit of full cooperation demonstrated in the analysis is the stability in the revenue stream over time, even for countries with highly volatile stock shares from year to year. Although it was not shown in this study, the market power gains from full cooperation is likely to also be significant. Smaller countries who are more vulnerable to volatile stock shares because of their lower stock endowment may be the countries who can benefit the most from full cooperation. Larger countries on the other hand may not be as vulnerable to revenue fluctuations given their larger endowments. The deciding point for political buy in for these larger countries will be the degree of improvement of revenue from full cooperation, and whether this will overcome the loss of control over fishing effort within their individual EEZ.

One important consideration is how to implement a single license system. Given the scale of the PNA and the fact that the two approaches are very similar, gradual implementation may be a prudent approach. Firstly, if the benefits are primarily to smaller countries, an initial step in implementation may be for smaller countries to sell a single license as a sub-coalition. This would give them greater market power relative to selling individually, while leaving the larger countries to continue with the local licensing. The coalition as a whole can be insulated from any unexpected issues which may arise. One possible problem with this is that forming a sub-coalition may cause stability issues within the PNA. Another possible intermediate step is to distribute the shares as licenses rather than revenue. This is technically equivalent to distributing revenue shares because theoretically the prices will be all the same. However, this would give countries control of their own finances and will not require the PNA to set up a central sale and finance facility.

One potential benefit of a single common license for all countries may be that it can serve as a catalyst for joint action on illegal fishing. The PNA members countries EEZ are very large, and the members do not have sufficient resources to monitor and patrol their waters. With a joint selling facility, countries may find it easier to contribute to a regional fund to combat the illegal fishing problem.

Chapter 7

Conclusion

A key aim of the PNA countries is to ensure the future health of the fishery, while maximizing the returns from this important resource. This thesis is an attempt to contribute to this effort by examining developing models tailored specifically towards answering two key questions. The first question is whether a switch to output regulation from the current input regulation management scheme is justified. The standard model used to analyze fisheries management problems in the literature cannot identify any differences between the two management approaches as it predicts that harvest and revenue under both management schemes are identical. I introduce heterogeneity of fishing vessels into the standard textbook model for fisheries, which allows for distinction between the two models. The second question asks whether a single license for the entire coalition could be a superior approach to license sales as compared the current practice of members selling country specific licenses.

In Chapter 3 I develop the model for a single fishery. I show that in this single country case, revenue from output regulation is always higher relative to input regulation. In Chapter 4, I extend this model to a two country case. Under ideal conditions, output regulation is still predicted to yield higher income levels. However, in this multi-country setting each fishing vessel has to choose which country to buy licenses from. This additional dynamic reveals that without the assumption of perfect information for the fishery manager, achieving the target harvest and stock levels set by the manager can be very difficult. A key consideration is the methods used to set the prices. Together these two cases suggests that selling a single licenses would greatly simplify the management of the fishery. However, a key consideration is the mechanism used to share the revenue as well as the stability of the revenue stream over time.

In Chapter 5, I compare the returns from selling a single global license relative to individual local licenses by developing a revenue sharing mechanism that can incorporates both approaches. The result show that a single license yields not only yields greater revenue levels, but also a more stable revenue stream over time.

There are three general implications from this study. First, a clear recommendation for a switch to harvest based licenses from the VDS may not be relevant. Output regulation for a single country setting will always yield higher revenue levels for the fishery manager selling license to fishing vessels. However, this result is not a straightforward extension to the multi-country setting. Assuming costs of fishing are constant across countries, output regulation may not be supportable. This implies that some countries may not be able to sell all of their licenses, and other countries might be pressured to sell more. Second, the results strongly suggest consideration of a single license that gives fishing vessels access to all countries. A single license will yield consistent and higher revenue streams over time. Such a case would be equivalent to a single country, and so output regulation over the VDS is clearly recommended and would yield higher income levels. The final implication is that more research needs to conducted to validate these results and examine conditions necessary to support these results. A logical next step is the analysis of empirical data within the framework provided in this study. One key issue to address is whether monitoring systems have improved enough to a level where harvest from fishing vessels can be correctly measured. Without this prerequisite, output regulation will not work.

The PNA and the VDS is a unique example of a multilateral agreement for cooperative management of a dynamic resource that has been successful. This dissertation is an attempt to provide insight into some issues that could build on this success, to improve the income levels from this resource to the PNA members. At the very least, it is the authors hope that it demonstrates how complex this problem is, and provoked thought and discussion about these issues.

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