

TRANSBOUNDARY MANAGEMENT OF A FISH STOCK UNDER
CLIMATE VARIABILITY: THE CASE OF PACIFIC SARDINE IN
THE CALIFORNIA CURRENT ECOSYSTEM

by

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Abstract

The time variant/asymmetric distribution of a fish stock caused by ocean climate variability is one of the challenges that must be overcome to establish cooperative management of a transboundary fish stock. Pacific sardine (*Sardinops sagax*) exhibits extreme decadal variability in its abundance and geographic distribution that corresponds to water temperature regime shifts within the California Current Ecosystem. It is a transboundary fish stock and targeted by Mexican, American and Canadian fisheries, and the three countries do not currently have a cooperative management arrangement. This thesis explores the economic and conservation consequences of non-cooperative management, and the potential benefits of full/partial cooperative management of Pacific sardine, and studies the stability of cooperative management under ocean climate variability. The core of the thesis is presented in Chapters 2-4, with an introduction given in Chapter 1 and a conclusion in Chapter 5. Appendix A and B provide background information on Pacific sardine and the Pacific sardine fishery, respectively.

Chapter 2 develops a three-agent bioeconomic framework to investigate the impact of ocean climate variability on stock abundance and geographic distribution. A game theoretic analysis was conducted to evaluate the conservation and economic benefits of various management strategies. The results show that under a regime of ocean climate variability, a country having a dominant share of the resource within its waters cannot achieve effective unilateral conservation for optimal economic benefits due to the actions of free-riders.

Chapter 3 conducts simulations to evaluate the stability of full and partial cooperative management of Pacific sardine under various climate variability scenarios. The results show that

in all scenarios, ocean climate variability is an obstacle to the formation of stable, fully-cooperative management of Pacific sardine fisheries as operated by the three countries.

Chapter 4 estimates the cost of delaying cooperative management of this fishery, and how costs are incurred due to such delays. The results suggest that the cost of delaying cooperative management is significant for a country having a dominant share, while countries that have minor shares gain economic benefits from delaying cooperative management.

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Statement of Co-Authorship

Chapters 3, 4 and 5 have been prepared as stand-alone manuscripts for submission to a peer-reviewed journal. They are currently all under review. I am, however, the senior author on all three papers, and I assume primary responsibility for the design, implementation, analysis, and writing of the co-authored papers. Dr. Sam Herrick Jr. from the U.S. National Marine Fisheries Services, Southwest Fisheries Science Center and Dr. Rashid Sumaila, my supervisor, are my coauthors for the three papers.

CHAPTER 1. INTRODUCTION

1.1 Introduction

A fishery consists of interaction, through fishing, between a fish resource and humans. Since fish are a renewable natural resource, in theory, they can provide ongoing benefit to society if conservation is embraced in order to sustain adequate parental stocks. The consumptive benefits of a fishery can be divided into two types. First, they provide food. Second, they generate income opportunities directly (e.g., fishing) and indirectly (e.g., processing, distribution). Inevitably, there are always uncertainties compounding the complexities inherent in the interactions between a fisheries resource and humans that inhibit society's ability to maximize the economic benefits while ensuring that a fishery is sustainable.

As has been well documented over the past several decades, ocean climate variability, which occurs on inter-annual and decadal scales in the marine environment, has added significant uncertainties and complexities to many fisheries. The consequences of oceanic climate variability affect fish stocks, directly and indirectly, by a combination of an increase or decrease in food availability and critical habitat (Brander 2007). Fish respond to these changes by 1) growing faster or slower their abundance; and 2) relocating to habitats more conducive to growth and reproduction. The consequence of these two responses jointly results in changes to local fish availability. As fishing activities have limited physical mobility due to economic and

political reasons, the impacts of any changes in the fish resources available for local fishing activities affect their catch levels.

As a result of increasingly anticipated changes in local fish availability caused by ocean climate variability, this has now become an emerging issue, particularly with regard to sustainable management of transboundary fish stocks. As such fish stocks are by definition exclusively shared by more than one country, and because of this sharing by multiple jurisdictions, a key feature of transboundary fisheries management is that one country's fishing activities affect the potential fishing opportunities of other countries (Munro 2002). In order to maximize and sustain the flows of benefits from such a fishery, cooperative management is both highly desirable and, in fact, necessary. The critical issues of such cooperation are how the countries will manage these fisheries resources, how they will share the fish stocks and the need to address these issues in self-enforcement agreements between or among the participating countries (Munro *et al.*, 2004; Hannesson 2006).

Such agreements must first guarantee that sufficient fish stocks are left unfished (escapement biomass) to ensure the continuous flow of future catches. Indeed, this escapement biomass defines the size of the permitted total allowable catch and is therefore a critical element of any

agreement. Secondly, based on escapement biomass, each country's share of the permitted catch needs to be set. When the destabilizations of abundance and spatial distribution of a transboundary fish stock caused by ocean climate variability, whether anticipated or not, is factored into a fishery, the challenges impacting the willingness and ability of the participants to come to an agreement on fisheries management become considerably more complicated. Yet they must be overcome, as the probable outcomes of non-cooperative management (competitive fishing activities on a single fish stock by more than one country) include degraded economic benefits, collapse of the fish stock, and even extinction of the fish stock. Further, attempts to unilaterally manage a fishery by an individual country usually lead to dissipation of any economic benefits the fish stock is capable of generating, while increasing the risk of its extinction (Munro 2007; Miller and Munro 2004).

1.2 Background

The northern stock of the Pacific sardine (*Sardinops sagax*) is considered to be a transboundary fish stock. Its habitat is the California Current Ecosystem (CCE), and it is distributed within the waters of three countries - Mexico, the U.S. and Canada – and fished exclusively by them. Hereafter, the term Pacific sardine refers to this northern stock.

Throughout the last century, Pacific sardine has exhibited extreme sensitivity to climate regime shifts in terms of its abundance and distribution (Emmett *et al.*, 2005). Warm regimes enhanced the abundance of Pacific sardine and expanded its distribution between Baja California, Mexico in the south and Canadian waters off Southern Vancouver Island in the north. Cold regimes lessened abundance and restricted distribution to waters within southern California in the U.S. and Baja California in Mexico.

Such variability has complicated fisheries management of Pacific sardine. Between the late 1940s and 1970s, a cold regime shift in the CCE, combined with overfishing, resulted in the collapse of Pacific sardine resources (Herrick *et al.*, 2006). As abundance decreased, the spatial availability of the resource to commercial fisheries shifted from a wide range over Canada (British Columbia), the U.S. (Washington, Oregon, California) and Mexico (Baja California), to a limited southern region encompassing southern California and Mexico (Hill *et al.*, 2007). Ultimately, direct fisheries in the U.S. for the Pacific sardine were closed in 1973. However, beginning in the 1980s, a warm regime shift in the California Current resulted in a more favourable environment for Pacific sardine. With conservation efforts, stocks recovered to levels not seen since the 1940s, and Pacific sardine reappeared in the waters off the Northwest U.S. (Oregon and Washington) and Canada (McFalane *et al.*, 2000). In 1986, direct fisheries

for the Pacific sardine were reopened in the U.S. Canada removed Pacific sardine from its endangered species list and reopened an official fishery in 2003. Subsequently, economic interests in the Pacific sardine stock have been rising equally in the three countries. However, due to the dominating biological uncertainties, up until now management of the Pacific sardine resource has not benefited from economic analyses. Moreover, although dynamic changes in the abundance and distribution of the Pacific sardine, as a result of continuing ocean climate variability, are anticipated, there is no agreement for cooperative management of Pacific sardine between Mexico, the U.S. and Canada.

1.3 Application of game theory to analyze transboundary fisheries

Game theory is a tool that analyzes strategic interactions between multiple players, where participants are involved in cooperative and non-cooperative strategies. It has been widely applied to the analysis of transboundary fisheries resources (e.g., Munro 1979; Munro 1990; Sumaila 1997; Armstrong and Sumaila 2001; Bjorndal and Lindroos 2004; Lindroos 2004) with positive results. Essentially, a game consists of 1) a set of agents (e.g., countries); 2) a set of strategies; and 3) a set of payoffs (benefits) from each given strategy. Cooperative management includes self-enforcement agreements between countries, in which countries aim to maximize and share in the overall benefit from the fisheries resource. Outcomes of cooperative

management of fisheries resources should, in theory, be equivalent to the benefits that would accrue to a sole owner. In non-cooperative management, each country acts with rational self-interest to maximize solely its own benefits from the resource, but the economic and biological (conservation) outcomes depend on what all countries do. Although game theory has the potential to be a powerful tool for the analysis of transboundary fish stocks, it has never been used to explore how distribution and abundance of a fish stock may be affected by ocean climate variability.

1.4 Outline of the dissertation

This dissertation consists of three separate studies of transboundary fishery management under climate variability and focuses on Pacific sardine in the CCE. The collective purpose of the studies is to improve our understanding of transboundary fisheries management as impacted by climate variability, and to promote cooperative management of Pacific sardine by Mexico, the U.S. and Canada by revealing the potential economic loss due to non-cooperation.

Chapter 2 explores the potential conservation and economic outcomes of non-cooperative, partial cooperative, and full cooperative management by Mexico, the U.S. and Canada of the Pacific sardine fishery when faced with ocean climate variability. The objective is to provide

fishery managers and policy makers with information on the probable economic consequences of a human induced collapse of the resource when climatically-induced changes in the abundance and distribution of the Pacific sardine are expected to complicate fisheries management.

Chapter 3 focuses on the stability of full and partial cooperative management strategies of Pacific sardine under ocean climate variability. It should be noted that an important emerging issue in transboundary fisheries management is the stability of potential cooperative agreements when impacted by ocean climate variability. Catch sharing rules are usually based on static spatial distribution of a fishable stock and assume its fixed availability in a participating country's waters. Uncertainties in fish distribution arising from ocean climate variability, therefore, have the potential to create incentives to deviate from cooperative management for those countries that have more abundant fish. In contrast, for countries where the availability of fish decreases, the possibility exists that the motivation for conservation and the fostering of sustainable fishery operations may be lost as fish disappear from their waters. The objective of this chapter is to help provide directions toward robust cooperative management of the Pacific sardine in the face of probable ocean climate variability.

Chapter 4 focuses on the costs of delaying cooperative management of Pacific sardine. The economic losses that occur from ineffective management of a transboundary fish stock that is affected by ocean climate variability result in large part from delaying the implementation of cooperative management. Unfortunately, recognition and confirmation of changes in a fish stock caused by ocean climate variability take time, yet these observations are needed to predict anticipated future changes. Further, negotiations to establish cooperative management take additional time because of likely conflicts in economic and political interests. These difficulties all serve to delay the adoption of cooperative management, and hence add to the loss of potential economic benefit, while at the same time increasing the risk of stock collapse. The objective of this chapter is to reveal the potential costs of delaying the implementation of cooperative management.

Chapter 5 synthesizes the three studies contained in this dissertation and summarizes the findings. The results presented in the three chapters clearly reveal not only the potential loss of the economic benefits that can be derived from the Pacific sardine fishery under non-cooperation, but also the risk that the Pacific sardine stock will collapse within the 35 year time horizon of the analyzes.

Appendix A and B provide background information on biology of Pacific sardine and economic of Pacific sardine fisheries respectively. This information has been synthesized in Chapter 2, 3 and 4.

Since Chapters 2, 3, and 4 are prepared separately as academic articles, note that their methods sections and background descriptions, will be repetitive. The results of the dissertation challenge Mexico, the U.S. and Canada to implement cooperative management of the Pacific sardine stock that anticipates ocean climate variability. This is the management arrangement that would continue to provide positive economic incentives to each country despite changes in ocean climate variability and the size and distribution of Pacific sardine stocks in the CCE.

Chapter 1 references

Armstrong, C. W., and U. R. Sumaila. 2001. Optimal allocation of TAC and the implications of implementing an ITQ management system for the north-east arctic cod. *Land Economics* 77(3):350-59.

Bjorndal, T., and Lindroos, M. 2004. International management of north-sea herring. *Environmental and Resource Economics* 29(1): 83-96.

Brander, K.M. 2007. Global fish production and climate change. *Proceeding of National Academy of Science* 104(50): 19709-19714.

Emmett, R. L., and R. D. Brodeur, T. W. Miller, S. S. Pool, G. K. Krutzikowsky, P. J. Bentley, and J. McCrae. 2005. Pacific sardine (*Sardinops sagax*) abundance, distribution, and ecological relationships in the Pacific Northwest. *California Cooperative Oceanic Fisheries Investigations Report* 46:122.

Hannesson, R. 2006. Individual rationality and the “zonal attachment principal”: Three stock migrate models. *Resource and Environment Economics* 34: 229–245

Herrick S.F., K. Hill., and C. Reiss. 2006 "An optimal harvest policy for the recently renewed United States Pacific sardine fishery." In *Climate Change and the Economics of the World's Fisheries: Examples of Small Pelagic Stocks*. ed. Hannesson R, Barange M, Herrick S, editors. Glasgow UK: Edward Elgar; p. 126-150.

Hill, K. T., N. C. H. Lo, B. J. Macewicz and R. Felix-Uraga. 2007. Assessment of the Pacific sardine (*Sardinops sagax caerulea*) population for U.S. management in 2006. *NOAA Technical Memo. NOAA-TM-NMFS-SWFSC-386*. 75p.

Lindroos, M. 2004. Sharing the benefits of cooperation in the Norwegian spring-spawning herring fishery. *International Game Theory Review* 6(1):35-53

McFarlane, G. A., J. R. King, and R. J. Beamish. 2000. Have there been recent changes in climate? Ask the fish. *Progress in Oceanography* 47(2-4):147-169.

Miller, K.A., and G.R. Munro. 2004. Climate and cooperation: A new perspective on the management of shared fish stocks. *Marine Resource Economics* 19(3): 367-393.

Munro, G. R. 1979. The optimal management of transboundary renewable resources. *Canadian Journal of Economics* 12(3):355-76.

Munro, G. R. 1990. The optimal management of transboundary fisheries: Game theoretic considerations. *Natural Resource Modeling* 4(4):403-2.

Munro, G.R. 2002. The optimal management of transboundary renewable resources. *Fisheries Economics: Collected Essays*. Volume 2: 63-84.

Munro, G.R. 2007. Internationally shared fish stocks, the high seas, and property rights in fisheries. *Marine Resource Economics* 22(4): 425-443.

Munro, G.R., A. Houtte., and R. Willmann.2004. The conservation and management of shared fish stocks: Legal and economic aspects. FAO Fisheries Technical Paper, Rome Italy

Schweigert, J. F. 2002. Update COSEWIC status report on the pacific sardine *Sardinops sagax* in Canada. Committee on the Status of Endangered Wildlife in Canada, Ottawa.

Sumaila, U.R. 1997. Cooperative and non-cooperative exploitation of the Arcto-Norwegian cod stock in the Barents Sea. *Environmental and Resource Economics* 10, 147-165.

Sumaila, U. R. 1999. A review of game theoretic models of fishing. *Marine Policy* 23(1):1-10.

CHAPTER 2. FISHING GAMES UNDER CLIMATE VARIABILITY: TRANS- BOUNDARY MANAGEMENT OF PACIFIC SARDINE IN THE CALIFORNIA CURRENT ECOSYSTEM¹

¹ A version of this chapter has been submitted for publication. Ishimura, G. S. Herrick and U.R. Sumaila (2010) Fishing games under climate variability: transboundary management of Pacific sardine in the California Current Ecosystem

2.1 Introduction

The 1982 United Nations Convention on the Law of the Sea (UNCLOS) instituted a country's exclusive right to catch fish within its Economic Exclusive Zone (EEZ). Although such rights legally rest with individual coastal countries, it is well recognized that there are challenges when it comes to the conservation and management of transboundary fish stocks (Article 63(1): UN 1982)²; those stocks whose distribution or migration extends over more than one country's EEZ. Under these circumstances, attempts to unilaterally conserve and manage such stocks usually lead to dissipation of the economic rents the resource is capable of generating, while increasing the risk of its extinction (Miller *et al.*, 2004; Munro 2007). There are many fisheries in the world, however, where cooperative management and comprehensive agreements about the utilization of the stock might be possible if exclusive access rights are assigned to a limited number of countries (Clark 1990; Sumaila 1999).

We are now aware that oceanic climate variability³, which changes the inherent characteristics of the marine environment over time, often affects the distribution patterns (including migration) of transboundary fish stocks (Brander 2007). Oceanic climate variability changes the physical and ecological characteristics of the marine environment, which in turn affects food

² A transboundary fish stock is one type of shared fish stock. For details on types of shared fish stock, see Munro *et al.*, (2004).

³ We follow a definition of "climate variability" by Brander (2007): inter annual and decadal variability in the marine environment.

availability and the critical habitats for many marine organisms. Fish stocks typically respond to these changes by redistributing themselves within a habitat more conducive for growth and reproduction (Cheung *et al.*, 2009). Thus, changes in the marine environment induced by climate variability can threaten the stability of the spatial distribution for transboundary fish stocks.

2.2 Pacific sardine in the California Current Ecosystem

Pacific sardine (*Sardinops sagax*) is a case in point. It is a small pelagic schooling fish whose abundance and distribution within the California Current Ecosystem (CCE) is greatly influenced by climate variability. Throughout the last century, the northern stock⁴ of Pacific sardine exhibited extreme fluctuations in its abundance and distribution, which has largely been attributed to climate variability inherent in the CCE (Norton *et al.*, 2005; Herrick *et al.*, 2006).

The CCE extends up to southern Vancouver Island from Baja California and exhibits high biological productivity (Miller and Schneider 2000). Through the last century, the CCE has experienced shifts between warm and cold climate regimes reflected in changes in sea surface temperature (SST). Four regime shifts in the California Current are currently proposed and

⁴ It is widely recognized and accepted that at least three substocks of Pacific sardine inhabit the CCE (Felix-Uraga *et al.*, 2005a; 2005b). These are the 1) northern substock, which is found from northern Baja California to south-eastern Alaska, 2) southern substock whose distribution ranges from Baja California to southern California and 3) Gulf of California substock, which spends its life within the Gulf of California.

under discussion; 1925, 1947, 1977 and 1988/89. The years of 1925, 1947 and 1977 have been confirmed as major climate regime shifts in several papers (e.g. Mantua *et al.*, 1997; Hare and Mantua 2000), but climate changes in 1988/89 were relatively small and considered a minor regime shift (McFarlane *et al.*, 2000; Minobe 2000; Field 2005). These years characterized a warm regime from 1925 to the 1947, a cold regime between the 1940s and late 1970s, and a warm regime from 1977 to the present (McFarlane *et al.*, 2000). It may be too early to confirm, but several studies (e.g. Peterson *et al.*, 2006; McClatchie *et al.*, 2008) infer that the CCE reverted to a cold regime in the late 1990s.

The abundance and distribution of Pacific sardine is extremely sensitive to SST changes caused by the above ocean climate variability in the CCE (Hill *et al.*, 2007). Between 1934 and 1944, the estimated biomass of Pacific sardine varied between 1.2 million and 2.8 million tonnes and it was the most abundant fish in the CCE (Figure 2-1). Originally, overfishing was blamed for the collapse of Pacific sardine stock. Now, it is believed that the beginning of the cold regime shift in the CCE during the 1940s decreased the biological productivity of Pacific sardine and accelerated the collapse of the stock, along with intensive fishing pressure. The collapse of Pacific sardine has therefore been attributed to a combination of overfishing and lowered biological productivity reflected to the cold regime (Herrick *et al.*, 2006). The abundance of

Pacific sardine remained below 5,000 tonnes during the 1950s and 1960s. As the CCE shifted to a warm regime in the late 1970s, the Pacific sardine stock began to rebuild. It is estimated that the biomass peaked at 1.71 million tonnes in 2000. The estimated biomass in 2006 was 1.31 million tonnes. The total catch by Mexico, the U.S. and Canada has remained greater than 120,000 tonnes since 2000 (Hill *et al.*, 2007). The following analysis is based on the Pacific stock assessment by Hill *et al.* in 2007.

It is well recognized that SST in the CCE also influences changes the distribution of Pacific sardine, primarily the extent of its migratory range (Hill *et al.*, 2007). With a CCE warm water regime, sardines become more abundant and their migratory range extends further northward and vice versa as the water cools. This phenomenon largely explains why sardines disappeared from Canadian waters in the late 1940s, as the entire stock collapsed during the CCE cold regime of the 1940s through early 1970s. In 1974, a moratorium was declared for the California fishery because of the greatly reduced biomass (Herrick *et al.*, 2006). With a warm regime since the 1980s, the range of the sardine stock has again expanded northward, by showing up in waters off Oregon, Washington and British Columbia in the early 1990s (Schweigert 2002).

Currently only a few studies have attempted to establish a relationship between climate variability and the abundance/distribution of Pacific sardine. Jacobson *et al.* (2005) developed a surplus production, population dynamics model using environmental disturbances. The authors examined the effect of two factors on the environment carrying capacity of Pacific sardine, 1) sea surface temperature (SST), and 2) spatial expansion of habitat blocks (areas) of Pacific sardine. As either factor increased, the carrying capacity in the model increased and in turn the abundance of Pacific sardine is increased. While their study does not explain the detailed mechanism of environmental effects on the Pacific sardine stock, their model successfully showed the possibility of including environmental disturbances in the population dynamics of Pacific sardine. Agostini *et al.* (2007) examined the relationship between the reproductive success of Pacific sardine and zooplankton volume in the primary spawning ground off the California coast. Their study suggested that the predation of zooplankton, whose abundance fluctuated with SST, would limit the survival rate of Pacific sardine larvae, and could thus induce dramatic fluctuations in the abundance of Pacific sardine. This is currently the only proposed detailed mechanism showing environmental effects on the abundance of the Pacific sardine stock. Although the detailed mechanism through which the environment in the CCE affects Pacific sardine is still not fully known, fishery scientists and managers agree that the

sardine stock exhibits variability in abundance and geographical distribution in accordance with the decadal cold - warm regime shifts (Emmett *et al.*, 2005).

With the northward expansion of the sardine stock it is shared by pre-existing fisheries in Mexico and the U.S., and an emerging Pacific sardine fishery in Canada. Figure 2-2 shows the changes in landing share for the three countries since 1983. Although Canadian fishing started increasing when the directed fishery was reopened in 2003, Canada's share of the landings does not appear large (2 - 3 % of the total coast-wide landings). This small share is mainly because of the limited market and processing capacity for Pacific sardine in Canada. An increased availability of Pacific sardine in Canadian waters, along with continued development of processing facilities and product markets could motivate Canadian fisheries to expand their operations. With economic interest in Pacific sardine on the rise in all three countries, transboundary conflicts are likely to arise because of the time variant/asymmetric shares of Pacific sardine distribution among these countries under cold and warm water regimes in the CCE.

2.3 Game theoretic approach

Game theory is a tool for the analysis of strategic interactions between multiple players involving cooperative and non-cooperative games. It has been widely applied to situations involving transboundary fisheries resources (e.g., Munro 1979; Munro 1990; Sumaila 1995; Armstrong and Sumaila 2001; Bjorndal and Lindroos 2004; Lindroos 2004*a*). Cooperative management needs self-enforcement agreements among the countries in the game. Here, countries aim to maximize the joint net benefit from a fish stock. Under non-cooperative management, each country acts to independently maximize its own benefits from the fish stock. If all or most of the participating countries understand that the benefits accruing to them from cooperative management are superior to non-cooperative management, they can enter into a self-enforcement agreement for cooperative management. This logic infers that the outcomes from game theoretic analysis of a transboundary fish stock might be one of the most powerful instruments to accelerate the process of establishing an international cooperative management framework for a transboundary fish stock – i.e., the tri-national management of Pacific sardine by Mexico, the U.S. and Canada.

If there are more than two players in a game, then the possibility of partial cooperation among participants needs to be recognized, in what is called a coalition. A coalition can exist with the

number of participants being less than the total number in the fishery. This partial cooperative model has been applied to analyze various shared fish stocks (e.g., Kaitala and Lindroos 1998; Li 1998; Lindroos and Kaitala 2000; Pintassilgo 2003; Lindroos 2004a, b; Kronbak and Lindroos 2006; Kronbak and Lindroos 2007). The Pacific sardine fishery has three participating nations: Mexico, the U.S. and Canada. These countries may have diverse motivations for cooperation, depending on their conservation and economic perspectives. Therefore, a coalition game would be appropriate and valuable for the analysis of the tri-national management of Pacific sardine.

The core aim of this study is to explore the potential conservation and economic outcomes under various fishing strategies for Pacific sardine chosen by the three countries given different ocean climate variability scenarios. No attempt is made to estimate precise catch or economic outcomes of current fishery operations. Rather, the goal of this study is to illustrate the conservation and economic benefits possible from full and partial cooperative management given available information. Most coalition studies for sharing fisheries (e.g., Lindroos and Kaitala 2000) focus on the benefits from cooperation (e.g., the Shapley value) given constant environment conditions; our focus in this study will be on demonstrating the effects of ocean climate variability on the outcomes of the games. To do so, this study develops an analytical

framework for Pacific sardine fisheries that allows us to evaluate various international management strategies for the conservation of the Pacific sardine resource.

2.4 Methods

The foundations of our integrated model are ocean climate variability in the CCE and the abundance/biomass distribution of Pacific sardine. SST at the Scripps Institute of Oceanography pier, in La Jolla, California (SIO SST), is often used as an indicator of the decadal cold-warm shifts in the CCE. Hereafter, SST in this paper refers to SIO SST. Significant correlations between SST and abundance/biomass distribution of Pacific sardine have been demonstrated (Jacobson and MacCall 1995; Jacobson *et al.*, 2005; Herrick *et al.*, 2007) . This study accordingly presumes that SST is a major driver of the abundance and biomass distribution of Pacific sardine under the following conditions:

- 1) High SST (warm regime of the CCE): an increase in the abundance of Pacific sardine and a biomass distributional shift from south to north in the CCE.

- 2) Low SST (cold regime of the CCE): a decrease in the abundance of Pacific sardine and a biomass distribution only in the south.

Our stochastic model shows Pacific sardine population dynamics driven by SST and is formulated with four components: *a*) an SST development model; *b*) a biomass distribution model spread over the three countries; *c*) a model of the information available to decision makers regarding of the distribution of the biomass of Pacific sardine; and *d*) a population dynamics model driven by SST. We integrate these four models for the population dynamics of Pacific sardine and expected biomass distribution (Figure 2-3). The effects of each game are then evaluated using statistics that measure economic outcomes and conservation success based on the results of Monte Carlo simulations.

2.4.1 Sea surface temperature development model

We use a base trend of a SST (τ) described by Equation 2-1⁵;

$$2-1 \quad \tau_{y+1} = \tau_y + \mu + \sigma \Delta z_y$$

$$\Delta z_y \sim N(0,1)$$

⁵ Arnason (2007) used the same mechanism to study the economic impacts of climate change on fisheries.

where y is year. Equation 2-1 evaluates SST over time as the sum of two components: 1) a static trend part, μ , accumulated over time; and 2) a stochastic error term, Δz_y . Since the majority of oceanographic environmental changes are associated with thermo hydrodynamic phenomena, this stochastic time increment (or decrement) is appropriate. In this study, μ and σ are estimated at 0.044 and 0.602, respectively, obtained from the average annual SIO SST from 1970 to 2002, which is considered a warm regime period in the CCE. It usually takes more than a decade to verify warm and cold climate regimes in the CCE. The current climate, which might be the initial stage of a cold regime shift, is not confirmed yet. Therefore, the years from 1970 to 2002, which are already confirmed as a warm climate regime, are applied to estimate the ocean climate development. The value of $\mu = 0.044$ represents a 0.044°C increase in temperature with one time step. This study evaluates two scenarios for SST trends; 1) an increasing (time-increment) SST trend ($\mu = 0.044$) which characterizes the warm regime; and 2) a decreasing (time-decrement) SST trend ($\mu = -0.044$) which characterizes the cold regime. The nature of the climate regime shifts of CCE is based on decadal interchanges of warm and cold regime shifts (two or three regime shifts during the twentieth century). This study adopts a 35-year time trajectory within which either one warm or cold regime shift could occur and be appropriately applied.

2.4.2 Biomass distribution model

Observed increases (decreases) in Pacific sardine abundance in the past may have led to the geographical expansion (contraction) observed in its spatial distribution (e.g., basin model by MacCall 1990). Data are sparse, however, to estimate a density-dependent relationship between population abundance and the spatial distribution of Pacific sardine. Therefore, we model biomass distribution by assuming a direct relationship between SST and discrete biomass distributions over the EEZs of Mexico, the U.S. and Canada based on three descriptive facts:

- a) The current U.S. sardine fishery policy assumes a static distribution with 87 % of the northern stock of Pacific sardine staying in U.S. waters (California, Oregon and Washington) and 13 % staying in Mexican waters (PFMC 1998).
- b) Canadian management assumes a static distribution of 10% of the northern stock entering Canadian waters. This assumption is based on an analysis of historical catch and trawl survey data (DFO 2004).
- c) Around 1990, Pacific sardine reappeared in Canadian waters.

Based on the above observations and analyses, this study makes two assumptions about the relationship between SST and the biomass distribution of Pacific sardine:

- i) At an SST of 17.9 °C, which was the five-year average SIO SST in 1999, the biomass distribution shares of Pacific sardine for Mexico, the U.S. and Canada, respectively, are 13%, 78% and 9%.

- ii) At an SST of 17.5 °C., which was roughly the five-year average SIO SST in 1992, the biomass distribution shares of Pacific sardine for Mexico, the U.S. and Canada, respectively, are 20%, 77% and 3%.

The biomass distribution model for Pacific sardine is assumed to be a discrete three-box model, see Equation 2-2. With changes in SST, the sardine biomass is distributed between Mexico (*MX*), the U.S. (*US*) and Canada (*CA*) in a discrete manner. The general pattern of the distribution of Pacific sardine within country w (D_w) relative to the others is assumed to be linear when the SST (τ) goes below the low threshold level (τ_{low}). We set different high and low threshold levels for Mexico ($\tau_{high_{MX}} = 18.3$ and $\tau_{low_{MX}} = 15$) and the U.S. ($\tau_{high_{US}} = 21.5$ and $\tau_{low_{US}} = 17.5$), with Canada having the residual thresholds;

$$2-2 \quad \left\{ \begin{array}{l} D_{MX,y} = \max \left[0, \min \left\{ 1, (\tau_{high_{MX}} - \tau_y) / (\tau_{high_{MX}} - \tau_{low_{MX}}) \right\} \right] \\ D_{US,y} = (1 - D_{MX,y}) \cdot \max \left[0, \min \left\{ 1, (\tau_{high_{US}} - \tau_y) / (\tau_{high_{US}} - \tau_{low_{US}}) \right\} \right] \\ D_{CA,y} = 1 - D_{MX,y} - D_{US,y} \end{array} \right.$$

$$s.t. \quad 0 \leq D_{w,y} \leq 1$$

$$D_{MX,y} + D_{US,y} + D_{CA,y} = 1$$

where w is country and y is year. In the simulations, we set the initial SST at 17.9° C, and the biomass at 1.2 million tonnes, which are approximate five-year averages for 1999 covering a period which has been confirmed as during a warm climate regime. Again it usually takes more than a decade to verify warm and cold climate regimes in the CCE. The biomass shares for Mexico, the U.S. and Canada, respectively, are 13%, 78%, and 9%. Our intention in this study is not to estimate the biological reference points, and this is the reason approximate SST and biomass already confirmed as warm ocean regime are applied. Our assumed biomass distribution model demonstrated that changes in Mexican, the U.S. and Canadian biomass shares were related to changes in the SST (Figure 2-4).

2.4.3 Information model for biomass distribution

The biomass distribution of Pacific sardine is the key variable determining each country's policy for the utilization of the Pacific sardine resource. We incorporate an auto-correlation function into the estimation of the expected biomass share for each country, based on the assumption that changes in the distribution of Pacific sardine are based on existing and past time series of biomass distributions. This is expressed as:

$$\begin{aligned} 2-3 \quad \hat{D}_{w,y} &= \rho \cdot D_{w,y} + (1-\rho)\hat{D}_{w,y-1} \\ &s.t. \quad 0 \leq \hat{D}_{w,y} \leq 1 \\ &\hat{D}_{w,0} = D_{w,0} \end{aligned}$$

where $\hat{D}_{w,y}$ is an expected distribution at year y in country w , and ρ is the auto-correlation weighting factor. The value of the weighting factor (ρ) captures the information delay regarding biomass distribution. For example, $\rho = 1$ implies that the expected biomass distribution of this year is identical to this year's true biomass distribution, and $\rho = 0$ implies that the expected distribution is not updated from the previous year's distribution. The magnitude of the weighting factor affects the information accumulation by each country, and subsequent fishing. In the simulations, we assume symmetric information for the three

countries and arbitrarily set the weighting factor at $\rho = 0.5$. In addition, we set ρ to values of 0, 0.25, 0.75 and 1.0 to conduct a sensitivity analysis on the impacts of changes in the conservation indicator on the results of our analysis.

2.4.4 Population dynamics model driven by SST

We assume that the fish stock migrates from a spawning area to each country's fishing grounds and then returns to their spawning ground for reproduction. Successful reproduction of Pacific sardine, therefore, depends on ample escapement biomass from the fisheries. Fishing is assumed to occur after reproduction and occurs simultaneously in each country's fishery.

Jacobson *et al.* (2005) developed a surplus production model for Pacific sardine with environmentally dependent components. This model expresses the aggregated productivity of individual growth and reproduction and has a continuous functional form, which was originally developed as the Gompertz-Fox model (Fox 1970). From this Gompertz-Fox model, the environmentally dependent surplus production model is described as:

$$G(S) = -e\eta S \ln\left(\gamma \frac{S}{I}\right)$$

2-4

where S is an escapement biomass which is a management strategy in this study. e is Euler's number (2.78), η and γ are constants, and I is an environmental factor. The environmental factor is varied over time and affects the carrying capacity. A key assumption is that the carrying capacity changes in proportion to environmental factors. A constant, η , expresses the relative magnitude of the maximum productivity over the carrying capacity. We adopted an SST for year (τ_y) generated with Equation 2-1 as an environmental factor (I). Because the Jacobson *et al.* model only used limited available biomass data, the Bayesian estimations for η (0.036) and γ (2.55) have been estimated using *WinBug* (Lunn *et al.*, 2000) with updated biomass data from recent stock assessment results (from Hill *et al.*, 2007)⁶.

The biomass (B) for the next year ($y+1$) given escapement biomass (S) in year y can be described by the discrete surplus production function:

$$2-5 \quad B_{y+1} = S_y - e\eta S_y \ln \left(\gamma \frac{S_y}{\tau_y} \right)$$

$$2-6 \quad S_y = B_y - h_y^{Canada} - h_y^{U.S.} - h_y^{Mexico}$$

⁶ Jacobson's estimations in 2005 are a set of prior distributions. See detailed of the estimation in Jacobson *et al.* (2005).

where B_y is a biomass and h_y is catch at year y . The target catch (\hat{h}) is defined as the expected distribution (\hat{D}), the size of biomass and the escapement biomass (S).

$$\begin{aligned}
 \text{2-7} \quad \hat{h}_y^w &= \hat{D}_{w,y} \cdot B_y - S_{w,y} \\
 \text{s.t. } 0 &\leq \hat{D}_{w,y} \leq 1 \\
 \hat{D}_{MX,y} + \hat{D}_{US,y} + \hat{D}_{CA,y} &= 1
 \end{aligned}$$

Due to time-variant biomass distribution and information delays regarding the biomass distribution, the target catch (\hat{h}) might be more than the amount of fish available in each country's water. The catch in a given year by the three countries (Mexico, the U.S. and Canada), therefore, is expressed as:

$$\begin{aligned}
 \text{2-8} \quad h_y^w &= \min \{ D_{w,y} \cdot B_y, \hat{h}_y^w \} \\
 \text{s.t. } 0 &\leq D_{w,y} \leq 1 \\
 D_{MX,y} + D_{US,y} + D_{CA,y} &= 1
 \end{aligned}$$

In the simulations, the annual fishing capacity for each country is neglected. Since global demand for sardines is strong and on the rise, sardine fishing industries in each country have positive incentives to expand their fishing capacities. Therefore, setting current maximum

catches would not reveal all possible losses of benefits rising from cooperative management. Moreover, since our focus is on the effects of ocean climate variability on distribution and biomass, we did not consider a stochastic process into the population dynamics.

Explicit assumptions with this surplus production approach are: *a*) the fishing sectors in all of these countries are homogeneous and *b*) simultaneous fishing takes place in all three countries, where the catch is a fraction of the existing biomass. Also, the biomass is distributed according to given allocations or spatial availability of the biomass within each country.

2.4.5 Structure of the games

Three countries, Mexico, the U.S. and Canada, are exclusively involved in the Pacific sardine fisheries. Besides the case of singletonnes, in which each country acts independently, we considered three possible coalition structures for the Pacific sardine fisheries. These are:

Coalition 1: (MX,US,CA), grand coalition;

Coalition 2: (MX,US), (CA), coalition of Mexico and the U.S.;

Coalition 3: (MX), (US,CA), coalition of the U.S. and Canada.

When a coalition consisting of two countries (coalition 2 or 3) exists, then the two countries in the coalition act as one agent. Therefore, this case can be simplified into a two-agent model. The payoffs for each coalition, called characteristic functions of the coalition game, are affected by how the non-member behaves. The fact that a two-country coalition among three countries makes the non-member country behave as a singleton (under the assumed objective function of a singleton, discussed below), will define the overall outcomes. Note that we did not consider a coalition of Mexico and Canada due to their geographical separation. Using the above three coalitions, we evaluated five games:

- Game I) Non-cooperative game: (MX) (US) (CA);
- Game II) Cooperative game with fixed shares of individual catch shares for the three countries: grand coalition: (MX,US,CA)_f;
- Game III) Cooperative game with dynamic shares of the individual catch shares for the three countries: grand coalition (MX,US,CA)_d;
- Game IV) Coalition of Canada and the U.S.: MX,(US,CA); and
- Game V) Coalition of the U.S. and Mexico: (MX,US),CA.

The difference between Game II and III is flexibility of the individual catch shares. In Game II, which has the subscript 'f', a fixed share of the individual catch equivalent to the initial biomass distribution means some countries may not fill their individual catch shares because of the time-variant biomass distribution of Pacific sardine. At the same time, some countries may have more Pacific sardine available than their individual catch share. Game III, which has the subscript 'd', assumes dynamic transferable individual catch shares between countries so that full utilization of the optimal catch is achievable. We assume fixed shares of the individual catch shares within coalition members for Game IV and V. For coalitions, individual catch shares are determined as a fixed share.

For the non-cooperative game (Game I) and singletons in the coalition games, the non-cooperative objective function with consideration of the asymmetric share of biomass is assumed. These will be introduced in the next sections. In our 35-year time horizon game, we assume countries stay with the same strategy and no country deviates from full cooperation or coalitions once the game has started.

2.4.6 Objective function in cooperative game

In the cooperative games (II and III, and in the coalitions in IV and V), we assume that the countries act cooperatively as the sole owner of the fish stock and seek to maximize joint benefits from the use of the Pacific sardine resource by adjusting the level of escapement biomass, S . The objective function that maximizes the present value through time, $f_{solo,y}$ at year y is:

$$2-9 \quad \max \quad f_{solo,y}(S_y^*) = p \cdot (B_y - S_y^*) + \frac{d \cdot p \cdot G(S_y^*)}{1-d}$$

where d is the discount factor, and $G(S)$ is the surplus growth function in Equation 2-5. p is a constant net economic price per unit catch (0.03 USD per pound). The first term expresses the economic benefits from the current catch and the second term expresses the future economic benefit (see Hannesson 2005). Much of Pacific sardine catch is destined for global markets, in which there are competitive substitutes for Pacific sardines. The catch level of Pacific sardine thus does not have a major influence on its ex-vessel price. The reasoning of the constant economic cost⁷ also draws from the work of MacCall (1976, 1990) and Radovich (1973, 1976, 1981), in which it is argued that, as the reduced Pacific sardine biomass contracts into a smaller

⁷ Hannesson *et al.*, (2009) also applied the net economic value for Pacific sardine catch.

area, it becomes more available there, and the fishery may not experience noticeable changes in catch per unit effort. This condition implies that assuming a constant cost per unit catch is reasonable rather than cost being inversely related to the abundance of fish.

Note that the escapement biomass level is subject to non-negativity and feasibility constraints that insure the condition, $0 \leq S \leq B$. For maximization of the objective function under sole ownership, the optimal escapement biomass (S_y^*) at year y is calculated using the first order condition of Equation 2-9:

$$2-10 \quad S_{solo,y}^* = \frac{\tau_y}{\gamma} e^{-\left(1 + \frac{1-d}{d\eta}\right)}$$

2.4.7 Objective function in non-cooperative game with major/minor player model

We modify the objective functions developed by Hannesson (2005) for non-cooperative games by using the objective function structure with the expected distribution:

$$2-11 \quad \max \quad f_{w,y}(S_{w,y}^*) = p \cdot (\widehat{D}_{w,y} \cdot B_y - S_{w,y}^*) + \frac{\widehat{D}_{w,y} \cdot d \cdot p \cdot G(S_{w,y}^*)}{1-d}$$

Hannesson (2005) studied games, involving one transboundary fish stock that migrates between two countries using a Schaefer production function, where the major player (country) has the largest share of the fish stock ($D_{major} > 0.5$), and is therefore assumed to have an incentive to conserve the stock for future benefits. However, a minor player (country) with a smaller share of the fish stock ($D_{minor} < 0.5$) is assumed to have an incentive to immediately liquidate the fish stock. When the distribution between the two countries is equal ($D = 0.5$), it is assumed that both countries act jointly as a sole owner and try to maximize the benefits through time. There are two complementary assumptions for the maximization problem under asymmetric shares:

- 1) The minor player has an incentive to fish the biomass level down to zero ($S_{w,y}^{Minor*}$); and
- 2) the major player has an incentive to leave the stock in the ocean until the fish stock size reaches the level that maximizes net present value of the benefits.

Building on Hannesson's study, this paper develops a game theoretic model based on the Gompertz-Fox population dynamics model with environmental disturbances. The optimal escapement biomass that maximize discounted profit for major and minor country are calculated as:

2-12

$$\begin{cases} S_{w,y}^{Major*} = \frac{\tau_y}{\gamma} e^{-\left(1 + \frac{1-d}{d\eta\hat{D}_{w,y}}\right)} & \text{if } \hat{D}_{w,y} > 0.5 \\ S_{w,y}^{Minor*} = 0 & \text{Otherwise} \end{cases}$$

Hannesson's analysis was for a two-agent model, where the biomass distribution clearly defined major/minor positions except when the two countries' shares of the distribution are the same ($D = 0.5$). In our three-agent model, however, it is possible for the biomass shares of the distribution of all countries to be less than 0.5, in which case all countries act as minor players. This could lead to the depletion of Pacific sardine. Our study applied these major/minor objective functions for a non-cooperative game (Game I), and as singletons in Game IV and V.

2.4.8 Summary performance statistics

Simulation outcomes are derived from 10,000 runs of 35-year time horizon of the games, with all trajectories differing from one another through stochastic variation from accumulated error terms in the above models. Conservation and economic outcomes are computed for each game.

2.4.9 Conservation indicator

This study calculates that the probability that the biomass falls below 10 % of the initial biomass (1.2 million tonnes) happens at least once over the 35-year time horizon of the games. Ten percent was chosen because of the biological resilience of Pacific sardine is high as shown by its history (less than 5,000 tonnes of a Pacific sardine during 1970s). The calculation shown as:

$$2-13 \quad P(B_y^k < \varphi B_0) = \frac{1}{10,000} \sum_{k=1}^{10,000} I(B_y^k < \varphi B_0)$$

where $I(B_y^k < \varphi B_0)$ is an indicator that equals 1 if the biomass during year y in simulation k is less than φ (0.1) of the initial biomass.

2.4.10 Economic indicators

The present value (PV) of net economic benefits over the 35-year time horizon of the games is taken as the measure of economic performance. The averages the present value of benefits received by each country under each game were calculated as:

$$2-14 \quad \overline{PV}_w = \frac{1}{10,000} \sum_{k=1}^{10,000} PV_w^k$$

where PV^k is the net present value in the k^{th} simulation:

$$PV_w^k = \sum_{y=1}^{35} d^{y-1} \cdot \pi_{w,y}^k$$

2-15

$$\pi_{w,y}^k = \dot{p} \cdot h_{w,y}^k$$

d is the discount factor, taken from the U.S. Office of Management and Budget, which uses a 3.2% discount rate for 35-year cost-effectiveness analysis, and $\pi_{w,y}^k$ is the economic benefits of fishing during year y in simulation k and country w . These conservation and economic indicators were used to evaluate results from the game simulations.

2.5 Results

2.5.1 SST, biomass distribution and carrying capacity

Table 2-1 shows the percentages of years that each country behaved as a major player based on the expected biomass distribution (see Equation 2-3). This result shows the domination of the U.S. as a major player in both scenarios (56% for increment SST and 55% for decrement SST). All countries acted as minor players for 3% and 9% of the years in increment and decrement SST scenarios, respectively.

2.5.2 Net present value

Compared to the non-cooperative game, both cooperative games suggested positive externalities through cooperative transboundary management (Table 2-2). A cooperative game with dynamic catch shares maximized the total PV at 461 and 444 million USD for the respective time-increment and decrement SST scenarios. The difference in the PVs between games II and III for each country reveals some conflicts. While the Mexican and Canadian PVs increased substantially after adapting dynamic individual catch shares (Table 2-2), the U.S. PV decreased significantly in both SST scenarios by - 40.7% in the increment SST scenario and - 39.5% in the decrement SST scenario. Note that the increase in total PV is relatively marginal as 8.7% and 7.0 % for increment and decrement SST scenarios, respectively.

For both SST scenarios, Mexico and Canada enhanced their present value when they act as free-riders, each one benefiting from others' collective conservation efforts. Mexico and Canada were particularly better off choosing to be a free-rider when the biomass distribution shifted into their waters (in the time-increment SST [warm water] scenario for Canada and time-decrement SST [cold water] scenario for Mexico). While free-riding, their role shifted from being a minor player to a major player, which increased their economic benefits particularly in the initial years of the simulation. Initially the free-rider acted as a minor player catching all available sardines

in its waters and enjoyed the spillover benefits from the coalition formed by the other two players. As more than half of the expected biomass distribution shifted into its waters, it acted as a major player trying to maximize the PV by considering future net benefits. In this regard, Mexico in the time-decrement scenario benefits by such free-rider activities and the potential conservation benefits of the US/CA coalition never materializes.

2.5.3 Conservation indicator

Significant conservation benefits were projected to result from cooperative transboundary management of the Pacific sardine resource (Table 2-3). Under both cooperative games and both SST scenarios, the probability that the biomass falls below 10% of the initial biomass was nil. On the other hand, results from the non-cooperative games, and to a lesser extent from the coalition games, suggest that stock depletion may occur. With $\rho = 0.5$, the resource is doomed (44% and 42% for the time-increment and decrement scenarios respectively) to be below 10% of the initial biomass under the non-cooperative scenario (Table 2-3).

The effects of the weighting factor on the information delay are explicit for the conservation indicators (Table 2-3). When $\rho = 0$, which implies that the expected biomass distribution is never updated, the conservation indicator the probability that the biomass falls below 10% of the

initial biomass in both ocean climate scenarios stays near zero. This is because the U.S. always behaves as a major player, and Mexico and Canada always catch smaller portions since their perceptions of biomass distribution are never updated from initial conditions. All cooperative managements in both ocean climate scenarios show robust results to the weighting factor. This suggests that cooperative management can be robust to uncertainty in information about biomass distribution.

2.6 Discussion

A major feature of this study is its utilization of game theory to look at transboundary conservation and management of Pacific sardine under ocean climate variability. Because of 1) the limited data available to quantify precise relationships between the distribution and abundance of Pacific sardine and climate variability in the CCE; and 2) the uncertainties of climate variability, it is reasonable to expect that our findings would not be completely within the realm of reference points or objectives of Pacific sardine management. Still, the results presented here anticipate the challenges facing tri-national/cooperative management of Pacific sardine by Mexico, the U.S. and Canada. Moreover, we deem our model useful for educating those charged with the conservation and management of the Pacific sardine resource, even if from a unilateral perspective.

Clearly, the cooperative approach is most likely to approximate the superior results desired of transboundary conservation and management of the Pacific sardine resource. Outcomes from non-cooperative use of a transboundary resource are expected to be inferior from both an economic and resource conservation standpoint. These expectations are shown in our study for both ocean climate scenarios. Moreover, our major/minor player model under the non-cooperative game suggested that unilateral efforts toward conservation or ensuring sustainable fisheries by the dominating share holder of the joint resource would not be successful given competitive motivations of the additional players. Since our model shows considerable free-rider benefits being garnered by Mexico and Canada in the coalition games, both countries have substantial motivation to deviate from the cooperative game. Mexico as a free-rider, in the time-decrement SST scenario, particularly, enjoyed economic gain conservation efforts by the US-Canada coalition. In this regard, under this climate scenario, it is a key to encourage Mexico to agree to cooperative management to achieve better economic benefits and conservation of the Pacific sardine resources. Moreover, the harmful results projected for the non-cooperative game, might inspire both Mexico and Canada to engage in a cooperative conservation and management strategy.

Contradictory results between cooperative games with fixed shares and dynamic shares of the annual Pacific sardine individual catch shares suggest that the incentives to establish a dynamic transferable individual catch share system depend on the domestic resource utilization priorities and policies of each country. While Canada and Mexico would have incentives to establish a dynamic transferable individual catch share system, it is uncertain that U.S. has an incentive to establish such a system even if the appropriate side payment is achieved. In this regard, one of the most common fisheries policies is to generate employment in the fishing industry. Although transboundary conservation and management under a dynamic individual catch share system is likely to maximize total benefits, transferring individual catch shares may reduce direct employment levels in the fishing industry and indirect employment in related industries in the U.S. Other issues with a dynamic transferable individual catch share system have to do with the transaction costs of establishing a market for individual catch shares or devising a side payment system. Our results show that there are only marginal gains in total PV by facilitating such a system, although the gains and losses of each country are diverse. The results also indicate that there are challenges to establishing initial individual catch shares for a shared fish stock among the participating countries when the effects of climate variability are anticipated. Diverse interests and expectations regarding climate variability among the countries would add to the challenge of achieving cooperative transboundary conservation and management.

This study did not undertake to look at 1) other SST development scenarios, 2) the effects of initial shares under a major/minor player game, 3) delays in obtaining information or decision-making moving from non-cooperative to cooperative games and 4) stability of coalitions including partition function games. Our future studies will undertake these topics and continue to work toward establishing cooperative transboundary conservation and management of the Pacific sardine resource among Mexico, the U.S. and Canada.

Our study attempts to inform the multiple perspectives that are needed in the establishment of cooperative transboundary management of the Pacific sardine resource. We show: 1) outcomes from cooperative, free-rider and non-cooperative conservation and management strategies; and 2) how these outcomes are affected by disparity between the collective good and the self interests of the participating parties.

2.7 Conclusion

This study has developed a framework for projecting potential conservation and economic outcomes from transboundary conservation and management of the Pacific sardine resource by Mexico, the U.S. and Canada under conditions of climate variability. Despite limited data

available to quantify the precise relationships between Pacific sardine and climate variability in the CCE, the simple structure of our model gives us extreme flexibility to accommodate additional data that may become available in the near future, and allow even more precise predictions about probable future climate scenarios.

Brander (2007) pointed out that fishing and climate variability exert tightly correlated pressure on fish stocks and that fishery management needs to jointly consider both. Even as significant knowledge and research about Pacific sardine and climate variability is accumulated, we will never have perfect predictive ability to foresee changes in both climate variability in the CCE and subsequent abundance and biomass distribution of Pacific sardine within the three countries, Mexico, the U.S. and Canada. All we can do is to collectively manage fishing activities to achieve sustainable Pacific sardine fisheries. Our analysis indicates that unilateral efforts to maximize conservation and management benefits from Pacific sardine will not be successful. Under current circumstances, an international cooperative management scheme is urgently needed that considers both the total and country specific benefits from the conservation and management of Pacific sardine.

Table 2-1 The percentage of time that each country is a major player and percentage of time all countries are minor players (for $\rho = 0.5$).

	Mexico (%)	U.S. (%)	Canada (%)	All minor (%)
Increment SST scenario	9.8	56.0	31.1	3.1
Decrement SST scenario	25.0	55.1	10.9	9.0

Table 2-2 The distribution of average present values (million USD) for different games and SST scenarios. Bold numbers show free-rider values. Note that the average total present values slightly may differ from the sum of the three countries due to rounding.

a) Time-increment SST scenario

		Present value for the net benefit for 35-year simulation (million USD)			
	Characteristic functions	Mexico	US	Canada	Total
Game I: Non-cooperative	(MX), (US),(CA)	108	68	152	327
Game II: Cooperative with fixed share	(MX,US,CA) ^f	40	322	61	424
Game III: Cooperative with dynamic share	(MX,US,CA) ^d	89	191	181	461
Game IV: Coalition of US and CA	MX,(US,CA)	175	105	156	436
Game V: Coalition of MX and US	(MX,US),CA	74	94	253	422

b) Time-decrement SST scenario

		Present value for the net benefit for 35-year simulation (million USD)			
	Characteristic functions	Mexico	US	Canada	Total
Game I: Non-cooperative	(MX), (US),(CA)	149	66	107	321
Game II: Cooperative with fixed share	(MX,US,CA) ^f	80	306	29	415
Game III: Cooperative with dynamic share	(MX,US,CA) ^d	170	185	89	444
Game IV: Coalition of US and CA	MX,(US,CA)	234	104	76	415
Game V: Coalition of MX and US	(MX,US),CA	145	88	182	416

Table 2-3 Conservation indicators (the probability that the biomass falls below 10% of initial biomass at least once over the 35-year simulation), and the sensitivity of our results on ρ (the weighting factor of the information delay for biomass distribution).

a) Time-increment SST scenario

ρ	<i>0</i>	<i>0.25</i>	<i>0.5</i>	<i>0.75</i>	<i>1.00</i>
Game I: Non-cooperative	0.00	0.43	0.44	0.51	0.59
Game II: Cooperative with fixed share	0.00	0.00	0.00	0.00	0.00
Game III: Cooperative with dynamic share	0.00	0.00	0.00	0.00	0.00
Game IV: Coalition of US and CA	0.00	0.03	0.01	0.01	0.01
Game V: Coalition of MX and US	0.00	0.05	0.03	0.02	0.02

b) Time-decrement SST scenario

ρ	<i>0</i>	<i>0.25</i>	<i>0.5</i>	<i>0.75</i>	<i>1.00</i>
Game I: Non-cooperative	0.00	0.41	0.42	0.47	0.57
Game II: Cooperative with fixed share	0.00	0.00	0.00	0.00	0.00
Game III: Cooperative with dynamic share	0.00	0.00	0.00	0.00	0.00
Game IV: Coalition of US and CA	0.00	0.03	0.01	0.01	0.01
Game V: Coalition of MX and US	0.00	0.03	0.02	0.01	0.01

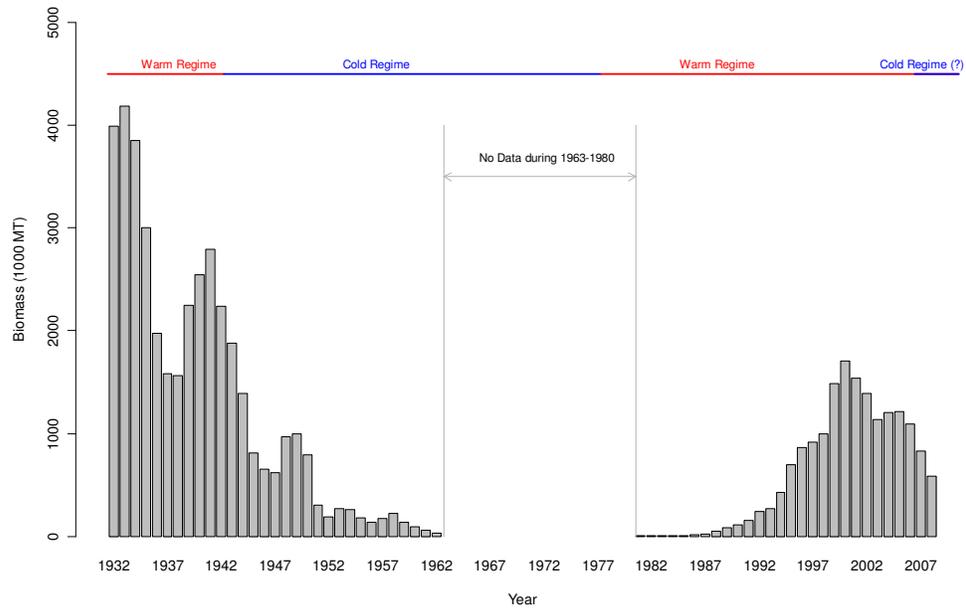


Figure 2-1 Biomass changes of Pacific sardine over time (biomass data from Hill *et al.*, 2009) and the climate regime in the California Current ecosystem.

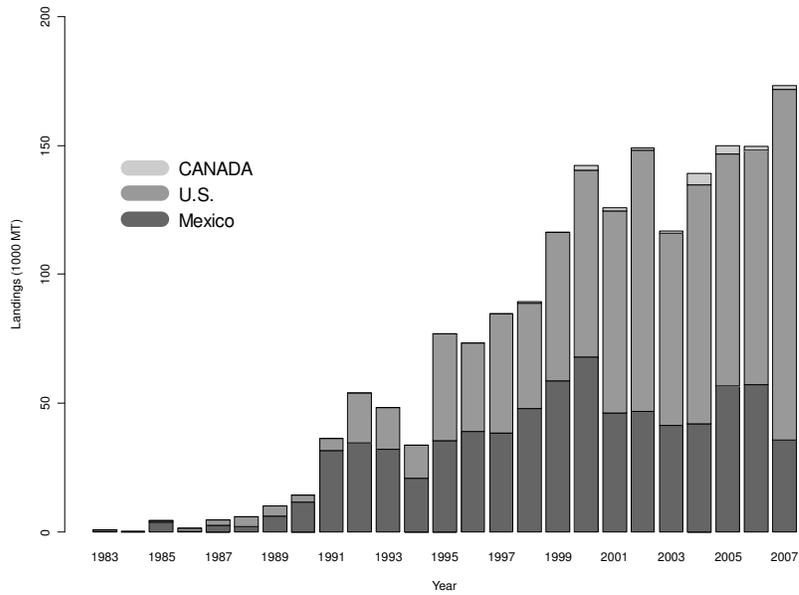


Figure 2-2 Landing changes of the Pacific sardine resource among three countries over time: Mexico, the U.S. and Canada (biomass data from Hill *et al.*, 2009).

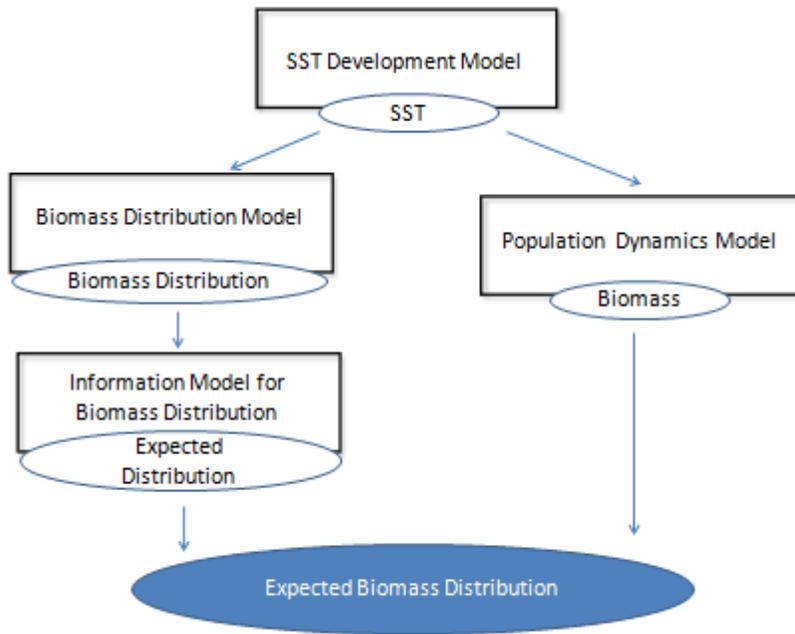


Figure 2-3 Diagram for the calculation of the expected biomass distribution.

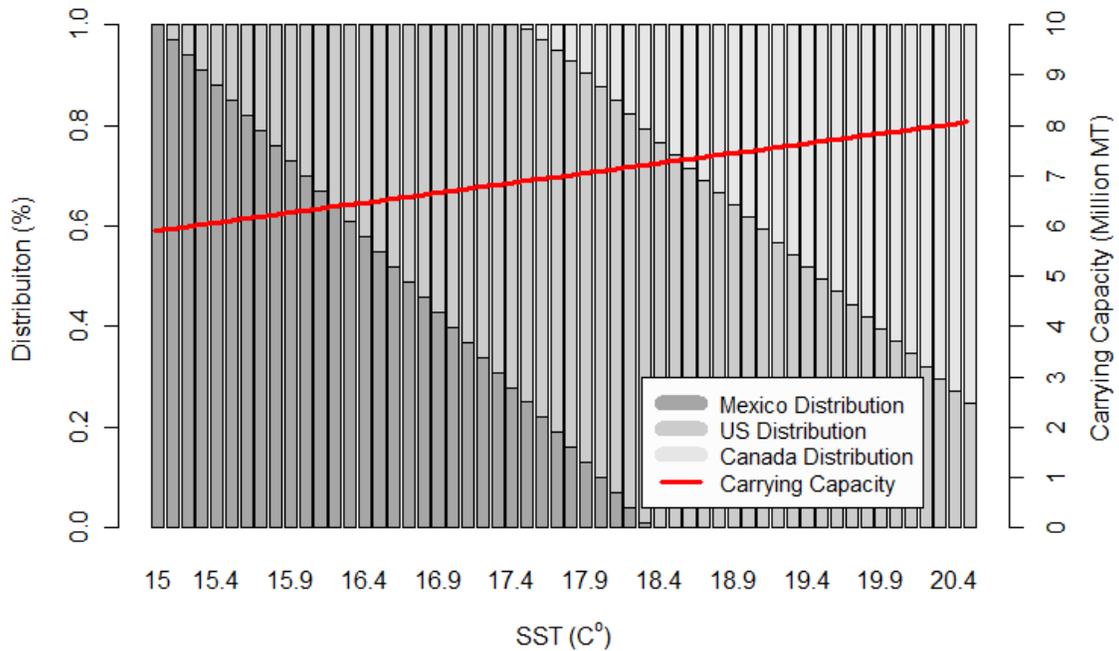


Figure 2-4 Development of the modeled biomass distribution and carrying capacity in accordance with the SST.

Chapter 2 references

Armstrong, C. W., and U. R. Sumaila. 2001. "Optimal allocation of TAC and the implications of implementing an ITQ management system for the north-east arctic cod." *Land Economics* 77(3):350-59.

Agostini, V.N., A. Bakun, and R.C. Francis. 2007. Larval stage controls on pacific sardine recruitment variability: High zooplankton abundance linked to poor reproductive success. *Marine Ecological Progress Series* 345: 237-244.

Arnason, R. 2007. Climate change and fisheries: Assessing the economic impact in Iceland and Greenland. *Natural Resource Modelling* 20(2): 163-197.

Brander, K.M. 2007. Global fish production and climate change. *Proceeding of National Academy of Science* 104(50): 19709-19714.

Bjorndal, T., and M. Lindroos, 2004. International management of north-sea herring. *Environmental and Resource Economics* 29(1): 83-96.

Cheung, W.W.L., V.W.Y. Lam, J.L.Sarmiento, K. Kearney, R.Watson, and D. Pauly. 2009. Projecting global marine biodiversity impacts under climate change scenarios. *Fish and Fisheries*: DOI: 10.1111/j.1467-2979.2008.003153.x.

Clark, C.W. 1990. *Mathematical bioeconomics: The optimal management of renewable resources*. : Wiley-Interscience.

DFO (Fisheries and Oceans Canada). 2004. Stock status report 2004/037. Report 037.

Emmett, R. L., R. D. Brodeur, T. W. Miller, S. S. Pool, G. K. Krutzikowsky, P. J. Bentley, and J. McCrae. 2005. Pacific sardine (*Sardinops sagax*) abundance, distribution, and ecological relationships in the pacific northwest. *California Cooperative Oceanic Fisheries Investigations Report* 46:122.

Felix-Uraga, R., V. M. Gomez-Munoz, C. Quinonez-Velazquez, F. N. Melo-Barrera, and W. Garcia-Franco. 2005a. On the existence of pacific sardine groups off the west coast of Baja California and southern California. *California Cooperative Oceanic Fisheries Investigations Report* 45:146-151.

Felix-Uruga, R., C. Quinonez-Velazquez, K. T. Hill, V. M. Gomez-Munoz, F. N. Melo-Barrera, and W. Garcia-Franco. 2005b. Pacific sardine (*Sardinops sagax*) stock discrimination off the west coast of Baja California and southern California using otolith morphometry. *California Cooperative Oceanic Fisheries Investigations Report* 46:113-121.

Field, J. C. 2005. Application of ecosystem-based fishery management approaches in the northern California current. Ph.D dissertation the University of Washington.

Fox, W. W. 1970. An exponential yield model for optimizing exploited fish populations. *Transactions of the American Fisheries Society* 99:80-88.

Hannesson, R. 2005. Global warming and fish migrations. *Institute for Research in Economics and Business Administration Report* N01/05.

Hannesson, R., S. Herrick, and J. Field. 2009. Ecological and economic consideration in the conservation and management of the Pacific sardine (*Sardinops sagax*). *Canadian Journal of Fisheries and Aquatic Science* 66(5): 859-868.

Hare, S.R., and N.J. Mantua. 2000. Empirical evidence for north pacific [climatic] regime shifts in 1977 and 1989. *Progress in Oceanography* 47(2-4): 103-145.

Herrick S., K. Hill, and C. Reiss. 2006. An optimal harvest policy for the recently renewed United States Pacific sardine fishery. in *Climate Change and the Economics of the World's Fisheries: Examples of Small Pelagic Stocks*. ed. Hannesson R, Barange M, Herrick S, editors. Glasgow UK: Edward Elgar. p126-150.

Herrick, S., J. Norton, J.E.Mason, and C. Bessey. 2007. Management application of an empirical model of sardine-climate regime shifts. *Marine Policy* 31(1): 71-80.

Hill, K. T., L. D. Jacobson, N. Lo, M. Yaremko, and M. Cege. 1999. Stock assessment of pacific sardine for 1998 with management recommendations for 1999. *California Department of Game and Fish Report* 99-4.

Hill, K. T., N. C. H. Lo, B. J. Macewicz, and R. Felix-Uruga. 2007. Assessment of the Pacific sardine (*Sardinops sagax caerulea*) population for U.S. management in 2006. *NOAA Technical Memo. NOAA-TM-NMFS-SWFSC-386*. 75p.

Hill, K. T., N. C. H. Lo, B. J. Macewicz, and R. Felix-Uraga. 2009. Assessment of the Pacific sardine resources in 2008 for U.S. management in 2009. forthcoming as NOAA Technical Memo.

Jacobson, L.D., and A.D. MacCall. 1995. Stock-recruitment models for pacific sardine (*Sardinops sagax*). *Canadian Journal of Fisheries and Aquatic Science* 52(3): 566-577.

Jacobson, L.D., S.J. Bograd, R.H. Parrish, R. Mendelsohn, and F.B. Schwing. 2005. An ecosystem-based hypothesis for climatic effects on surplus production in California sardine (*Sardinops sagax*) and environmentally dependent surplus production models. *Canadian Journal of Fisheries and Aquatic Science* 62(8): 1782-1796.

Kaitala, V., and M. Lindroos. 1998. Sharing the benefits of cooperation in high seas fisheries: A characteristic function game approach. *Natural Resource Modeling* 11(4):275-99.

Kronbak, L. G., and M. Lindroos. 2006. An enforcement-coalition model: Fishermen and authorities forming coalitions. *Environmental and Resource Economics* 35(3):169-194.

Kronbak, L. G., and M. Lindroos. 2007. Sharing rules and stability in coalition games with externalities. *Marine Resource Economics* 22(2):137-154.

Li, E. 1998. Cooperative high-seas straddling stock agreement as a characteristic function game. *Marine Resource Economics* 13(4):247-58.

Lindroos, M. 2004a. Restricted coalitions in the management of regional fisheries organizations. *Natural Resource Modeling* 17(1):45-69.

Lindroos, M. 2004b. Sharing the benefits of cooperation in the Norwegian spring-spawning herring fishery. *International Game Theory Review* 6(1):35-53.

Lindroos, M., and V. Kaitala. 2000. Nash equilibrium in a coalition game of the Norwegian spring-spawning herring fishery. *Marine Resource Economics* 15(4):321-39.

Lunn, D.J., A. Thomas, N. Best, and D. Spiegelhalter. 2000. WinBUGS - a Bayesian modeling framework: concepts, structure, and extensibility. *Statistics and Computing* 10:325--337.

- MacCall, A. D. 1976. Density dependence of catchability coefficient in the California Pacific sardine, *Sardinops sagax caerulea*, purse seine fishery. *California Cooperative Fisheries Investigations Reports*, 18: 136-148.
- MacCall, A. 1990. Dynamic geography of marine fish populations. University of Washington Press, Seattle USA.
- Mantua, N.J., S.R. Hare, Y. Zhang, J.M. Wallace, and R.C. Francis. 1997. Pacific interdecadal climate oscillation with impacts on salmon production. *Bulletin American Meteorological Society* 78(6): 1069-1080.
- McClatchie, S., R. Goericke, J.A.Koslow, F.B. Schwing, S.J. Bograd, R. Charter, W. Watson, N. Lo, K. Hill, J.Gottschalck, M. L'Heureux, Y. Xue, W.T. Peterson, and R. Emmett, 2008a. The state of the California current, 2007-2008: La Niña conditions and their effects on the ecosystem. *California Cooperative Oceanic Fisheries Investigations Report*. 49.
- McFarlane, G. A., J. R. King, and R. J. Beamish. 2000. Have there been recent changes in climate? Ask the fish. *Progress in Oceanography* 47(2-4):147-169.
- Miller, A. J., and N. Schneider. 2000. Interdecadal climate regime dynamics in the north pacific ocean: Theories, observations and ecosystem impacts. *Progress in Oceanography* 47(2-4):355-379.
- Miller, K., G.R. Munro, and T. Bjoerndal. 2004. Climate, competition and the management of shared fish stocks, *Report of Institute for Research in Economics and Business Administration*, 33.
- Minobe, S. 2000. Spatio-temporal structure of the pentadecadal variability over the north pacific. *Progress in Oceanography* 47(2-4): 318-408.
- Munro, G. R. 1979. The optimal management of transboundary renewable resources. *Canadian Journal of Economics* 12(3):355-76.
- Munro, G. R. 1990. The optimal management of transboundary fisheries: Game theoretic considerations. *Natural Resource Modeling* 4(4):403-26.

Munro, G.R. 2007. Internationally shared fish stocks, the high seas, and property rights in fisheries. *Marine Resource Economics* 22(4): 425-443.

Munro, G.R., A. Houtte, and R. Willmann, 2004. The conservation and management of shared fish stocks: Legal and economic aspects. FAO Fisheries Technical Paper 465.

National Research Council 1998. Improving fish stock assessments. Washington, D.C : Committee on Fish Stock Assessment Methods, Ocean Studies Board, Commission on Geosciences, Environment, and Resources, National Academy Press.

Norton, J. G. and J. E. Mason. 2005. Relationship of California sardine (*Sardinops sagax*) abundance to climate-scale ecological changes in the California Current Ecosystem. *California Cooperative Oceanic Fisheries Investigative Report* 46: 83-92.

Pacific Fisheries Management Council. 1998. The Coastal Pelagic Species Fishery Management Plan. Pacific Fishery Management Council, Portland, OR.

Peterson, B., R. Emmett, R. Goericke, E. Venrick, A. Mantyla, Ralstonnes., K.A. Forney, R. Hewitt, N. Lo, W. Watson, J. Barlow, M. Lowry, F. Chavez, and W.J. Sydeman, 2006. The state of the California current, 2005-2006: Warm in the north, cool in the south. *California Cooperative Oceanic Fisheries Investigative Report* 47: 30.

Pintassilgo, P. 2003. A coalition approach to the management of high seas fisheries in the presence of externalities. *Natural Resource Modeling* 16(2): 175-197.

Radovich, J. 1973. A challenge of accepted concepts involving catch per unit effort data. *Proceedings of the Annual Meeting of the California-Nevada Chapter of the American Fisheries Society*, 6 pp.

Radovich, J. 1976. Catch-per-unit-of-effort: fact, fiction or dogma. *California Cooperative Fisheries Investigations Reports*, 18: 31-33.

Radovich, J. 1981. The collapse of the California sardine fishery: what have we learned?' in M. H. Glantz and J. D. Thompson (eds), *Resource Management and Environmental Uncertainty*, New York, US: John Wiley & Sons.

Schweigert, J. F. 2002. Update COSEWIC status report on the Pacific sardine *Sardinops sagax* in Canada. Committee on the Status of Endangered Wildlife in Canada, Ottawa.

Sumaila, U. R. 1995. Irreversible capital investment in a two-stage bimatrix fishery game model. *Marine Resource Economics* 10(3):263-83.

Sumaila, U. R. 1999. A review of game theoretic models of fishing. *Marine Policy* 23(1):1-10.

United Nation, 1982. "United Nations on the Law of the Sea", UN Doc. A/Cof.62/122.

**CHAPTER 3. CAN THERE BE STABLE, COOPERATIVE MANAGEMENT OF A
TRANSBOUNDARY FISH STOCK UNDER CLIMATE VARIABILITY? THE CASE
STUDY OF THE PACIFIC SARDINE FISHERY IN THE CALIFORNIA CURRENT⁸**

⁸ A version of this chapter has been submitted for publication. Ishimura, G. S. Herrick and U.R. Sumaila (2010) Can there be stable, cooperative management of a transboundary fish stock under climate variability? The case study of the Pacific sardine fishery in the California Current.

3.1 Introduction

Cooperative management of a fishery resource can play a significant role in the sustainability of a transboundary fish stock, i.e., one that is distributed (or migrates) within more than one countries' Exclusive Economic Zone (EEZ) and is exclusively shared by these countries. A common characteristic of a transboundary fish stock is that one country's fishing activities affect the potential catch opportunities of the other countries (Munro 2002). This means that participating countries' catch activities will 1) affect another country's economic return from a transboundary fish stock; and 2) interfere with the conservation activities for a transboundary fish stock by another country. Non-cooperative management, therefore, can lead to undesirable economic outcomes or even the depletion of a fish stock even if each country behaves in a rational manner. Cooperative management, where the joint benefit of all participating countries is maximized, has often been shown to be a better solution (e.g., Sumaila 1999).

The 1982 United Nations Convention on the Law of the Sea (Article 63(1): UN 1982) imposes a duty on countries participating in the fishing of a transboundary fish stock to negotiate for cooperative management of such stocks. This, however, does not impose requirements for these countries to reach a cooperative agreement (Munro *et al.*, 2004) or prescribe penalties for deviations from once-reached agreements on cooperative management. If countries sharing a fish stock are not able to reach an agreement, at best each country may attempt to manage the

part of a transboundary fish stock within their waters, often with poor results if the other participating countries fail to do so.

Ocean climate variability, both inter-annual and decadal, often induces significant changes in the physical and ecological dynamics of the marine environment (Brander 2007), and causes subsequent changes in food availability and critical habitats of a fish stock (e.g., Bakun 1998).

By seeking more conducive habitats for growth and reproduction, a fish stock's spatial distribution is often altered. For example, the North Atlantic Oscillation, one of the major drivers of ocean climate variability on earth, influences the abundance and the migration patterns of Norwegian spring-spawning herring in the Norwegian Sea (Alheit and Hagen 1997).

Perry *et al.* (2005) showed that the centers of distributions in eight fish species and the range limits for 4 species experienced warming-related northward shifts from 1977-2001 in the North Sea. Challenges for transboundary fisheries are anticipated where ocean climate variability affects fish distributions, and consequently fish availability within countries' EEZs.

An important emerging issue for transboundary fish stocks is the stability of cooperative management under conditions of ocean climate variability, as incentives for free-riding arise.

Stability in cooperative management can be defined as players not having incentives to deviate

from agreements, and have been discussed for high sea fisheries (e.g., Kronbak and Lindroos 2007; Pintassilgo 2003). Cooperative management of a transboundary fish stock requires agreements on the sharing rule of the catch gains from cooperation by the participating countries (Hannesson 2006a). While ocean climate variability causes dynamic changes in the fish stock distribution, catch sharing rules of a transboundary fish stock are usually based on static spatial distributions of a fishable fish stock available in the participating countries' waters (e.g., the zonal attachment principal for the European Union and Norway during the late 1970s: Hannesson 2006b). Uncertainties in fish distribution arising from ocean climate variability, therefore, create incentives to deviate from cooperative management for countries that have more fish in their waters than before due to ocean climate variability. In countries where the availability of fish may decrease with ocean climate variability, the possibility exists that the motivation for the conservation of the stock and any sustainable fishery operation may be lost due to the disappearance of fish within their waters.

Only a limited number of studies have looked at ocean climate variability with respect to transboundary fish stocks. Laukkanen (2003) studied sequential fishing game situations for Northern Baltic salmon with environmental disturbances in recruitment, and concluded that there were significant effects of environment variability on maintaining cooperative

management; her study did not include uncertainties in fish distributions. McKelvey *et al.* (2006) studied bi-national management of a transboundary fish stock with incomplete information, and assumed a stochastically split fraction of a transboundary fish stock among the two countries' waters. Miller and Munro (2004) undertook a case study of Canada - US Pacific salmon management – another fishery that experiences abundance and distribution changes reflected to ocean climate variability. Miller (2007) studied the stability of regional fishery management organizations for highly migratory fish stocks (e.g., tuna), and concluded that a key to a country's incentive for cooperative management is anticipated changes to fish stocks. Ishimura *et al.* (2010) incorporated the distribution and abundance uncertainties of a transboundary fish resource under ocean climate variability in a case study using Pacific sardine fisheries. Brandt and Kronbak (2010) undertook the analysis on the stability of full and partial cooperative management of three country groups for Baltic cod fisheries under climate changes. They concluded that climate change may reduce the resource rent from Baltic cod and lessen the feasibility of stable cooperative conservation and management of the resource. Until now, as far as we know, this is the only study that assesses the stability of cooperative management under ocean climate variability with a practical case study of fisheries.

The northern stock of Pacific sardine in the California Current Ecosystem (CCE) is a transboundary stock whose biological productivity is affected by ocean climate variability and is exclusively fished by Mexico, the U.S. and Canada. Hereafter, Pacific sardine in this paper refers to the northern stock of Pacific sardine. Although the detailed mechanisms through which temperature affects Pacific sardine are still not fully known, researchers and managers agree that Pacific sardine exhibit variability in abundance and a time variant/asymmetric geographic distribution in accordance with decadal cold-warm regime shifts , which is one type of climate variability, in the CCE (Rodriguez-Sanchez *et al.*, 2002; Emmett *et al.*, 2005). The warm regime of the CCE increases the abundance of Pacific sardine and causes a distributional shift in biomass that spans south to north in the CCE, including Canada, the entire U.S. and Mexico west coast. The cold regime of the CCE decreases the abundance of the Pacific sardine stock and reduces its distribution almost entirely to southern California (U.S.) and Baja California (Mexico).

Despite impending conflicts from continued uncertainties as to the distribution and abundance of Pacific sardine under ocean climate variability in the future, there is no formal cooperative management agreement in place among the three countries. With economic interests in Pacific sardine on the rise in all three countries, transboundary conflicts are likely to occur because of

the time variant/asymmetric distribution of Pacific sardine among countries under cold and warm regimes in the CCE. It would be beneficial to all participants in the fishery to encourage the establishment of agreements on cooperative management for the conservation and sustainable use of Pacific sardine resources.

Ishimura *et al.* (2010) developed a Pacific sardine fisheries model accounting for changes in distribution and abundance in response to ocean climate variability by using the Pacific sardine biomass data in the 2006 stock assessment (Hill *et al.*, 2007). Using a range of potential ocean climate scenarios, they examined economic and biological outcomes under full and partial cooperative and non-cooperative management. While they successfully modeled economic and biological outcomes, they did not account for stability of full and partial cooperative management. Further such analysis can play a significant role in establishing a cooperative management scheme by these three countries.

We are at an early stage of recognizing the effects of ocean climate variability on Pacific sardine, but it is reasonably anticipated that international conflicts caused by distribution uncertainties will arise. This study does not attempt to provide a precise estimate of economic and biological outcomes of current Pacific sardine fisheries. Rather, this study explores the stability of full and

partial cooperative management of Pacific sardine in the CCE, a transboundary stock with time-variant distributions caused by ocean climate variability. As in Lindroos and Kaitala (2000), we adopt two-stage coalition games with positive externalities as described by Yi (1997). In the first stage, countries form coalitions. In the second stage, coalitions engage in full and partial cooperative management given the coalition structure determined in the first stage. We further explore the stand-alone stability of a coalition as defined by Yi (1997), which is a coalition structure that no participant finds profitable to leave in order to form a one-country coalition, or singleton, if all other elements in a coalition structure are held constant. To examine this, our study follows the two stability criteria for coalitions applied for fisheries resource analysis by Lindroos and Kaitala (2000), 1) group rationality, where the total benefits from forming one coalition structure exceed the benefits from any other coalition structures; and 2) individual rationality, looking at whether any participating country in a coalition is better off deviating from the coalition. Here, the economic returns for each country are determined strictly by catch, restricted by fish availability within the country's waters as determined by ocean climate variability.

3.2 Material and methods

3.2.1 Background

Historically, landings of Pacific sardine have exhibited extreme variability with ocean climate changes in the CCE. Until the middle of the 1940s (warm regime), with an annual catch of about 500,000 tonnes, and a peak of 700,000 tonnes, the Pacific sardine resource fueled the largest fishery in North America. The depletion of the Pacific sardine stock began in 1945. Between the late 1940s and 1970s, a cold regime shift in the CCE, combined with extreme fishing, resulted in the collapse of the Pacific sardine resource. Pacific sardine completely disappeared from Canadian waters, and were only found within the U.S. in southern California (Herrick *et al.*, 2007). As a result California instituted a moratorium on its direct Pacific sardine fishery in 1974 (Wolf 1992). In the mid 1980s, a warm regime shift in the CCE, along with fisheries closures, allowed the Pacific sardine resource to recover rapidly. From 1983 to 2007, the age 1+biomass of Pacific sardine increased about ten-fold (Figure 3-1a). Total coast-wide landings increased rapidly beginning in the early 1990s (Figure 3-1b) and have topped 100,000 tonnes since 1992. In 2007, total landings were 173,120 tonnes, the highest recorded since the recovery of the Pacific sardine resource (Hill *et al.*, 2008).

Due to dramatic changes in the stock's distribution, the structure of participants in the Pacific sardine fishery has changed over the decades. The Pacific sardine distribution during cold regimes (late 1940s-early 1970s) was primarily limited to southern California (U.S.) and Baja California (Mexico). As the resource was replenished during a warm regime beginning in the 1970s, its distribution expanded further northward into Northern California, Oregon (OR), Washington (WA) and British Columbia (BC), Canada. The distribution change brought new fishery opportunities to OR, WA and BC.

3.2.2 Game theory analysis

Game theory has been widely applied to the analysis of biological and economic outcomes of non-cooperative and cooperative management of transboundary fisheries resources since the first study by Munro (1979) (e.g., Munro 1990; Sumaila 1995; Armstrong and Sumaila 2001; Lindroos 2004a; Kronbak and Lindroos 2007). In non-cooperative management, each country acts with rational self-interest to maximize its own benefits from that part of a transboundary fish resource that is within its waters. Benefits from the cooperative management of a transboundary fisheries resource would have to be equivalent to those by a sole owner.

A coalition game over a shared fish stocks can occur when a coalition can form having a number of participants less than or equal to the total number of countries sharing the stock (e.g., Kaitala and Lindroos 1998; Li 1998; Lindroos and Kaitala 2000; Pintassilgo 2003; Lindroos 2004a, b; Kronbak and Lindroos 2006, 2007). Only in a situation where all countries behave rationally and recognize desirable biological and economic outcomes, is cooperative management stable (Nash 1953; Agüero and Gonzalez 1996). In a coalition game, participants deviate from cooperation if they stand to benefit more from deviation than from cooperation, hence satisfying the individual rationality constraints. Stability in each possible coalition is analyzed by examining outcomes and distributions among participants within a coalition by using the partition function approach, which associates benefits from each coalition with various sharing rules (e.g., core, Shapely value) within a coalition (Pintassilgo 2003; Kronbak and Lindroos 2007). There are only a limited number of studies where partition function games are applied to shared fishing resources (e.g., Pintassilgo, 2003; Kronbak and Lindroos, 2007). The aforementioned study by Brandt and Kronbak (2010) is currently the only study to analyze the stability of full/partial cooperative management under the effect of ocean climate change.

3.2.3 Model overview

Our Pacific sardine fisheries model is based on changes from stochastic models of ocean climate variability (i.e., sea surface temperature, SST) and a population dynamics model incorporating environmental effects on abundance and biomass distribution developed by Ishimura *et al.* (2010). The model incorporates objective functions for cooperative and non-cooperative management of fisheries by the three countries, using the optimal target escapement biomass as a control variable. This study simulates full, partial cooperative and non-cooperative management using the model in Ishimura *et al.* (2010), and further examines economic and biological outcomes with various ocean climate scenarios.

3.2.4 Ocean climate model

Sea surface temperature (SST) is often used as an indicator of ocean climate variability, in this instance, decadal cold-warm regime shifts in the CCE. Significant correlations between the SST at the Scripps Institute of Oceanography pier in La Jolla, California, USA (SIO SST) and the abundance and biomass distribution of Pacific sardine have been confirmed (Jacobson and MacCall 1995; Jacobson *et al.*, 2005; Herrick *et al.*, 2007). High SIO SST (warm regime of the CCE) corresponds to an increase in the biomass of Pacific sardine and its extension northward in the CCE. Low SIO SST (cold regime of the CCE) corresponds to a contraction in the

abundance of Pacific sardine from north to south. Ishimura *et al.* (2010) used the SIO SST as an index of climate variability for Pacific sardine. Hereafter, SST refers to SIO SST and is used as the index of ocean climate variability. The stochastic SST development model is described as follows:

$$\tau_{y+1} = \tau_y + \mu + \sigma\Delta z_y$$
$$\Delta z_y \sim N(0,1)$$

where y is time. Equation 3-1 calculates SST over time as the sum of two components: 1) a constant driven part μ accumulated over time; and 2) a stochastic error term Δz_y . As in Ishimura *et al.* (2010), this study adopts μ and σ values of 0.044 and 0.602, respectively, based on the trend of the annual average SIO SST from 1970 to 2002, which is considered a warm regime period in the CCE. While Ishimura *et al.* (2010) modeled only two SST trend scenarios, one increasing (time-increment) and one decreasing (time-decrement), this study examines four additional ocean climate scenarios by multiplying μ by two and three for both time-increment and decrement trends. Scenarios in this paper are then, 1) time-increment SST trend ($\mu = 0.044$); 2) time-increment SST trend ($\mu = 0.088$); 3) time-increment SST trend ($\mu = 0.132$); 4) time-decrement SST trend ($\mu = -0.044$); 5) time-decrement SST trend ($\mu = -0.088$) and 6) time-decrement SST trend ($\mu = -0.132$). We begin with an initial SST of 17.9°C, which is the

five-year average SIO SST between 1997 and 2001, which has previously been confirmed as a warm regime of the CCE. The character of climate regime shifts of the CCE is cyclical over a century (three regime shifts during the twentieth century). In this study, a 35-year simulation is conducted, which is appropriate for either one warm or cold climate regime shift, is applied.

3.2.5 Biomass distribution model

This study uses a simple discrete three-box model for the representation of the biomass distribution of Pacific sardine in the waters of Mexico, the U.S. and Canada (Equation 3-2).

With changes in the SST (τ) the Pacific sardine biomass is redistributed between Mexico (MX), the U.S. (US) and Canada (CA) in a discrete manner, and the distribution (D) expressed as:

$$3-2 \quad \begin{cases} D_{MX,y} = \min \left[1, (\tau_{high_{MX}} - \tau_y) / (\tau_{high_{MX}} - \tau_{low_{MX}}) \right] \\ D_{US,y} = (1 - D_{MX,y}) \cdot \min \left[1, (\tau_{high_{US}} - \tau_y) / (\tau_{high_{US}} - \tau_{low_{US}}) \right] \\ D_{CA,y} = 1 - D_{MX,y} - D_{US,y} \end{cases}$$

$$\text{s.t. } 0 \leq D_{w,y} \leq 1$$

$$D_{MX,y} + D_{US,y} + D_{CA,y} = 1$$

where w is country (MX, US or CA) and y is year. As in Ishimura *et al.* (2010), the general pattern of distribution of Pacific sardine within country w (D_w) relative to the others is assumed

to be linear when the SST (τ) goes between the low threshold levels ($\tau_{low_{MX}} = 15$ and $\tau_{low_{US}} = 17.5$) and high threshold level of the SST ($\tau_{high_{MX}} = 18.3$ and $\tau_{high_{US}} = 21.5$). As SST increases, the biomass expands northward so that in Mexican and the U.S. waters decrease, while the proportion in Canada increases (hence, the range of the stock biomass extends further northward during warm regimes). As the SST decreases, the biomass contracts southward so that the relative distribution in Mexico and the U.S. increases, and decreases in Canada decreases (hence, the southward shifts in the distribution during cold regimes). As in Ishimura *et al.* (2010), this study sets the initial biomass at 1.2 million tonnes and the initial biomass distribution for Mexico, U.S. and Canada, respectively, as 13%, 78% and 9%. The initial biomass distribution is based on a combination of current management assumptions.

3.2.6 Information model for biomass distribution

This study incorporates an auto-correlation function into the estimation of the expected biomass share for each country, based on the existing and past time series of biomass distribution:

$$\begin{aligned}
 \text{3-3} \quad & \hat{D}_{w,y} = \rho \cdot D_{w,y} + (1 - \rho) \hat{D}_{w,y-1} \\
 & \text{s.t. } 0 \leq \hat{D}_{w,y} \leq 1 \\
 & \hat{D}_{MX,y} + \hat{D}_{US,y} + \hat{D}_{CA,y} = 1
 \end{aligned}$$

$$\hat{D}_{w,0} = D_{w,0}$$

where $\hat{D}_{w,y}$ is an expected distribution at year y in country w , and ρ is the auto-correlation weighting factor. The value of the weighting factor (ρ) captures the information delay regarding biomass distribution. The magnitude of the weighting factor affects the information accumulation for each country, and subsequent fishing patterns. The smaller the weighting factor (ρ), the more delayed the information is on fish distribution. To examine the effect of information delay on the stability of cooperative management, we assume identical information in the three countries and arbitrarily set the weighting factors to $\rho = 0.5$. See sensitivity tests in Ishimura *et al.* (2010).

3.2.7 Biomass dynamic model

Population dynamics are described by a discrete surplus production model, which uses SST (τ) as the ocean climate index influencing the carrying capacity ($1/\gamma$). The biomass (B) for the next year ($y+1$) given the escapement biomass (S) for this year (y) can be described by the discrete surplus production function:

$$B_{y+1} = S_y - e\eta S_y \ln \left(\gamma \frac{S_y}{\tau_y} \right)$$

3-4

$$h_y = B_y - S_y$$

where e is a Euler's number (2.72); η and γ are constants. The estimations for η (0.04) and γ (2.55) are applied in this study (Ishimura *et al.*, 2010). Catch (h) is expressed as the difference between biomass (B) and the escapement biomass (S). The growth function of this model (the second term on the right hand side) was originally developed by Jacobson *et al.* (2005) from the Gompertz-Fox surplus production model (Fox 1970). The SST (τ_y) varies over time and affects the carrying capacity. A key assumption is that the carrying capacity changes in proportion to the SST. As the SST increases, the carrying capacity increases. Hence, the marginal productivity of the biomass increases. In the same manner, as the SST decreases, the carrying capacity decreases, and the marginal productivity of the biomass decreases. The escapement biomass (S) is a decision variable used to achieve maximum benefits from fisheries. Later, objective functions for cooperative and non-cooperative managements will explain how the escapement biomass is determined.

3.2.8 Economic outcomes-present value

The economic benefits of fishing during year y in simulation k and country w are expressed as:

$$\pi_{w,y}^k = p \cdot h_{w,y}^k$$

where p is a constant price per unit catch. This study assumes a constant unit economic benefit from the catch of Pacific sardine. We chose this approach because:

- 1) Much of Pacific sardine catch is destined for global markets, in which there are competitive substitutes for Pacific sardines. The catch level of Pacific sardine therefore does not have a major influence on its ex-vessel price.

- 2) With the tight schooling behavior of Pacific sardine we can assume that the production functions of catch by these countries is not influenced by global and local abundance of Pacific sardine. The reasoning of this draws from the work of MacCall (1976, 1990) and Radovich (1973, 1976, 1981), in which it is argued that, as the reduced Pacific sardine biomass contracts into a smaller area, it becomes more available there, and the fishery may not experience noticeable changes in catch per unit effort.

These conditions imply that assuming a constant price and cost per unit catch is reasonable⁹. As an approximate of net economic benefit, we therefore apply a constant net price for catch of

⁹ The constant economic value of the Pacific sardine catch was also applied in Hannesson *et al.*, (2009)

0.03 USD per pound, which is the average ex-vessel price in the U.S. between 1999 and 2005.

The present value (j) for a 35-year simulation is then calculated as:

$$3-6 \quad j_w = \sum_{y=1}^{35} \pi_{w,y}^k \cdot d^{y-1}$$

where d is the discount factor (0.97) taken from the U.S. Office of Management and Budget which uses a 3.2% discount rate.

$$3-7 \quad \bar{j}_w = \frac{1}{10,000} \sum_{k=1}^{10,000} j_w^k$$

The payoff for a coalition is calculated as the average present value (\bar{j}) over 10,000 simulations for each of the participating countries (w).

3.2.9 Biological outcomes

As a biological performance indicator, we calculate the probability that the biomass falls below 10% of the initial biomass (1.2 million tonnes) at least once over the 35-year time horizon of the model. Ten percent was chosen because it reflects the fact that the biological resilience of

Pacific sardine is high as shown by its history (less than 5,000 tonnes of a Pacific sardine during 1970s).

$$3-8 \quad P(B_y^k < 0.1B_0) = \frac{1}{10,000} \sum_{k=1}^{10,000} I(B_y^k < 0.1B_0)$$

Where $I(B_y^k < 0.1B_0)$ is an indicator that equals 1 if the biomass during year y in simulation k is less than 0.1 of the initial biomass.

3.2.10 Objective function

Countries, whether in a coalition or individually choose the level of optimal escapement biomass (S_y^*) at year y to maximize the present value of net benefits through time (Ishimura *et al.*, 2010):

$$3-9 \quad \max \quad f(S_y^*) = p \cdot (B_y - S_y^*) + \frac{d \cdot p \cdot G(S_y^*)}{1-d}$$

where $G(S)$ is the growth term in the surplus function (the second term in the right hand side in Equation 3-4). For maximization of the objective function under sole ownership, the optimal escapement biomass (S_y^*) at year y is calculated using the first order condition of Equation 3-9:

3-10

$$S_{solo,y}^* = \frac{\tau_y}{\gamma} e^{-\left(1+\frac{1-d}{de\eta}\right)}$$

3-11

$$h_{solo,y} = B_y - S_{solo,y}^*$$

This optimal escape biomass is applied as a decision variable for cooperative management and two- country coalitions.

Hannesson (2005) studied two-player games involving a transboundary fish stock with a time-variant distribution (share), where the major player (country) had the largest share ($\hat{D}_{major} > 0.5$), and an incentive to conserve the stock for future benefits and a minor player (country) had a smaller share ($\hat{D}_{minor} < 0.5$) and an incentive to immediately liquidate the fish stock. There are two complementary conditions for the maximization problem under asymmetric shares. The minor player has an incentive to fish the biomass level down to zero ($S^{Minor*} = 0$) and the major player has an incentive to leave the stock in the ocean until the fish stock size reaches a level that maximizes future benefits. Building on Hannesson's study, Ishimura *et al.* (2010) developed objective functions with the Gompertz-Fox population dynamics model for

environmental disturbances. The escapement biomass that maximizes present value is calculated as:

$$3-12 \quad \begin{cases} S_{w,y}^{Major*} = \frac{\tau_y}{\gamma} e^{-\left(\frac{1-d}{d\eta\hat{D}_{w,y}}+1\right)} & \text{if } \hat{D}_{w,y} > 0.5 \\ S_{w,y}^{Minor*} = 0 & \text{Otherwise} \end{cases}$$

This optimal escape biomass is applied as a decision variable for non-cooperative management and singletonnes in coalition games.

With the optimal escapement biomass, the target catch in year (y) for country (w) is

$$3-13 \quad \hat{h}_{w,y} = \hat{D}_{w,y} \cdot B_y - S_{w,y}^*$$

The catch for each country is determined by fish availability in country's water ($D_{w,y} \cdot B_y$) and;

$$3-14 \quad h_{w,y} = \min\{D_{w,y} \cdot B_y, \hat{h}_{w,y}\}$$

3.2.11 Game structure

The basis of this study is the examination of full and partial cooperative management by Canada, the U.S. and Mexico. We approach this by analyzing coalition games and examining seven possible coalition structures ($\{ \}$); 1) $\{\text{Canada, U.S., Mexico}\}_d$; 2) $\{\text{Canada, U.S., Mexico}\}_f$; 3) $\{\text{Canada, US}\}$; 4) $\{\text{U.S., Mexico}\}$; 5) $\{\text{Canada}\}$; 6) $\{\text{U.S.}\}$ and 7) $\{\text{Mexico}\}$. Coalition structure 1 and 2 are so called grand coalitions, and represents full cooperative management. The difference between coalition structure 1 and 2 has to do with the transferability of fishing access rights among the three countries if changes in the stock's distribution result from ocean climate variability. Coalition structure 1 establishes dynamic individual catch shares that are transferable between countries so that it is possible to achieve full utilization of the target catch given a redistribution of the shared stock (denoted by the subscription d). Coalition structure 2 fixes individual shares of the catch at the initial biomass distribution proportions (denoted by the subscription f). Having fixed shares of the target catch, as in coalition structure 2, means that some countries may not attain their absolute target catch amounts because of the time-variant distribution of Pacific sardine. At the same time, some countries may have more Pacific sardine than their individual catch shares.

In this study, we further assume that any country outside of a coalition adopts the aforementioned optimum escapement biomass for major/minor, where non-members behave as singletons (e.g., Lindroos and Kaitala 2000). Coalitions 3 and 4 are two-country coalitions with free-rider singletons. Note that a coalition of Mexico and Canada would not be feasible due to their geographical separation. This study, therefore, studies only two two-country coalitions, namely {Canada, US} and {U.S., Mexico}. Coalitions 5, 6 and 7 are so called singletons, and it represents non-cooperative management.

This study determines the payoffs of the coalition game by following Lindroos and Kaitala (2000). The values of a grand coalition (Coalitions structure 1 and 2) are:

$$3-15 \quad v(w_1, w_2, w_3) = \bar{J}^{w_1} + \bar{J}^{w_2} + \bar{J}^{w_3}$$

The value of a two-country coalition (Coalitions structure 3 and 4) is:

$$3-16 \quad v(w_1, w_2) = \bar{J}^{w_1} + \bar{J}^{w_2} \quad , \quad w_1 \neq w_2$$

The value of singletons (Coalitions structure 5, 6 and 7) is:

3-17

$$v(w) = \bar{J}_w, w \in \{\text{Canada, the U.S., Mexico}\}$$

These values are calculated and presented in the next section.

3.3 Results

3.3.1 Temperature and distribution changes

This study examines six scenarios of ocean climate variability. Without a stochastic error term, for the three time-increment SST scenarios, SST was assumed to increase by 1.5 °C, 3.1 °C and 4.7 °C by the end of 35-year period. In the same manner, for the three time-decrement SST scenarios, the SST was assumed to decrease by 1.5 °C, 3.1 °C and 4.7 °C by the end of the 35-year period. At the initial setting of 17.9 °C, the biomass distributions for Mexico, U.S., Canada were, respectively, 13%, 78% and 9%, with the U.S. as the major player ($D_{US} > 0.5$). As the SST increased and exceeded 19.4 °C, the major player position shifted to Canada. As the SST decreased over time and the SST fell below 16.7 °C, the major player position shifted to Mexico; between 16.7 °C and 19.4 °C, the U.S. held the major player position.

3.3.2 Economic outcomes

All payoff results derived from the simulations are summarized in Table 3-1. For all scenarios, grand coalitions with dynamic transferable catch shares ($\{\text{Canada, U.S., Mexico}\}_d$) yield the highest total payoffs among coalition members. Again, group rationality to maintain coalition structures is that the total benefits from forming one coalition structure exceed the benefits from any other coalition. From this aspect of group rationality, therefore, this implies that a grand coalition with dynamic transferable catch shares is more stable than other coalition structures for all scenarios. Non-cooperative management (singletons) for all scenarios is expected to lead to undesirable economic outcomes. These expectations are fulfilled – the total payoffs for non-cooperative managements were always the lowest.

While aspects of group rationality clearly demonstrate the relative stability of grand coalitions, implications of individual rationality differ. The most notable features relevant here were that payoffs for Canada and Mexico in both grand coalitions did not exceed the payoffs for free-riders in all scenarios. For example, in the time-increment SST scenario with $\mu = -0.044$ (Table 3-1 a-1), the payoff for Canada and Mexico in the grand coalition with dynamic transferable catch share ($\{\text{Canada, U.S., Mexico}\}_d$) were 181 and 89 million USD while the free-rider values were 253 and 175 million respectively. The requirement of stand-alone

stability (or equilibrium coalition structures) is that no country finds it profitable to deviate from its coalition to form a singleton coalition (Yi 1997; Pintassilgo 2003; Pintassilgo and Lindroos 2008). The implication is that a grand coalition can be stand-alone stable if and only if payoffs for each country exceed payoffs from free-ridings. Therefore, according to individual rationality, grand coalitions in this study are not stand-alone stable for all ocean climate variability scenarios.

Applying individual rationality to investigate two-country coalition structures is also complicated than for three-country coalitions (i.e., grand coalitions). For all time-increment SST scenarios, the total payoff exceeded the sum of payoffs from singletons for only the Canada and U.S. coalition ($\{Canada, US\}$). Hence, $\{Canada, US\}$ for time-increment SST scenarios is standalone stable. For example, $\{Canada, US\}$ in Table 3-1 a-1, Canada yielded 156 million USD and the U.S. yields 105 million USD. Both values exceed payoffs for Canada (152 million USD) and the U.S. (68 million USD) under non-cooperative management. The total payoffs from the other two-country coalition structures in time-increment SST scenarios did not exceed the sum of respective individual payoffs in the three-singleton case ($\{Canada\}$, $\{U.S.\}$, $\{Mexico\}$). For time-decrement SST scenarios, the total payoff for the Mexico and U.S. coalition ($\{U.S., Mexico\}$) yielded 264 million USD for $\mu = -0088$ and 294 million USD for μ

= - 0.132 which exceeded the sum of payoffs from singletonnes, 234 million USD and 253 million USD respectively. For time-decrement SST scenarios, where $\mu = - 0.044$, there were no two-country coalitions that could be characterized as stand-alone stable. Hence, stand-alone stability within the time-decrement SST scenarios where $\mu = - 0.044$ consisted of singletonnes, engaged in non-cooperative management.

3.3.3 Biological outcomes

The probability that the biomass falls below 10% of the initial biomass (1.2 million tonnes) at least once over the 35-year trajectory ($B_{<10}$) is presented on the right-hand columns in Table 3-1. Higher values of $B_{<10}$ suggest a higher risk of biomass depletion. The $B_{<10}$ probability term for singletonnes for all scenarios clearly showed that non-cooperative management leads to high risk of biomass depletion ($B_{<10} > 30.5\%$ for all scenarios).

3.4 Discussion

The purpose of this study was to examine the stability of full and partial cooperative management of a transboundary fish stock with time-variant distribution caused by ocean climate variability, specifically Pacific sardine in the CCE.

This study has clearly confirmed that time variant distribution uncertainties caused by ocean climate variability interfere with the ability of the three countries to achieve a grand coalition, which would maximize both the total payoffs and the conservation opportunities available through cooperative fishery management.

In time-increment SST scenarios that induce northward distributional shifts of Pacific sardine, only a two-country coalition formed by Canada and the U.S. had stand-alone stability. In these ocean climate scenarios, the stock biomass expands northward and enhances fish availability in Canadian waters. In this circumstance dominate shares of the stock enjoyed by Canada and the U.S. results in this coalition being stand-alone stable.

In contrast, in time-decrement SST scenarios, a two- country coalition formed by Mexico and the U.S. where $\mu = - 0.088$ or $- 0.132$ was stand-alone stable. In the time-decrement SST scenarios where $\mu = - 0.044$, only singletonnes satisfied the stand-alone stable conditions. In time-decrement SST scenarios, the fish distribution shifts southward and results in more fish in Mexican waters. The time-decrement SST scenario where $\mu = - 0.044$ did not bring enough fish into its waters to keep Mexico in a two-country coalition. This scenario showed that non-

cooperative management consisting of singletonnes was stable but led to less than desirable economic and resource conservation outcomes.

Side payments, which are positive incentives given by one or more countries/players in a game to other countries/players to induce the latter to join a cooperative agreement, can foster the formation of a grand coalition by the three countries in the game. For stand-alone stable two-country coalitions, for example, {CA, U.S.} in the time-increment scenario $\mu = 0.044$ (Table 3-1 a-1), if Canada and the U.S. were to provide a side payment to Mexico of more than 175 million USD (free-rider value for Mexico in this ocean climate scenario), Mexico would have an incentive to join a grand coalition. In addition to conservation benefits, the sum of economic benefits for Canada and U.S. ($461 - 175 = 286$ million USD) from a grand coalition can still exceed the pay-off from a two-country coalition (261 million USD). Side payments could foster a grand coalition for stand-alone stable two-country coalitions under all three time-increment SST scenarios and the time-decrement SST scenarios $\mu = - 0.088$ or $\mu = - 0.132$ (Table 3-1 b-2 and 3). In the time-decrement SST scenarios for $\mu = - 0.044$, the U.S., which is the largest beneficiary in a grand coalition, can take the initiative for side payments. For instance, looking at the time-decrement SST scenario $\mu = - 0.044$ (Table 3-1 b-1), if the U.S. guarantees Canada and Mexico at least 107 and 149 million USD, respectively, these two countries would stay in a

grand coalition and the U.S. would still gain 188 million USD ($188 = 444 - 107 - 149$) which would be much more than the pay-off for the U.S. in non-cooperative management. Therefore, side payments could be a powerful tool to facilitate the formation of a grand coalition.

Miller (2007) concluded that it is necessary to maintain a country's incentives to cooperate despite changes in fish availability. Our results revealed that the stand-alone stability of a grand coalition to exploit Pacific sardine can not be achieved based on ocean climate variability. However, our results suggest that side payments can be an incentive for cooperation. Brandt and Kronbak (2010) concluded that climate change has a negative effect on the resource rent from Baltic cod and would reduce the incentive for stand-alone stable agreements for this fishery. Our study showed that increased productivity under increasing SST would have a positive effect on the resource rent from Pacific sardine, and decreased productivity under a decreasing SST would have a negative effect on the resource rent. While two-country coalitions can be stand-alone stable for all increasing SST scenarios, two of the decreasing SST scenarios ($\mu = -0.088$ or $\mu = -0.132$ in Table 3-1 b-2 and 3) could attain a stand-alone stable two-country coalition. In the later case, the rapid southward contraction of the sardine stock makes Mexico the major country, and this makes the two-country coalition stand-alone stable. This is in contrast to Brandt and Kronbaks (2010) conclusions.

In this study we showed that, ocean climate variability prevents the Pacific sardine fisheries of Canada, the U.S. and Mexico from achieving stand-alone stability through transboundary cooperative management within a grand coalition. The only stand-alone coalition structure for the time-increment SST scenarios was the two-country coalition consisting of Canada and the U.S. ($\{Canada, US\}$). The Mexico and U.S. coalition ($\{Mexico, US\}$) was stable for the extreme time-decrement SST scenarios considered ($\mu = -0.088$ and $\mu = -0.132$), and was favorable in terms of reducing the risk of overexploitation of the sardine stock relative to non-cooperative management. Besides singletons, there is no stand-alone coalition for time-decrement SST scenarios for $\mu = -0.044$. Finally side payments from the stand-alone stable two-country coalition or the country that benefits most in a grand coalition can provide incentives to form a grand coalition.

3.5 Conclusion

A three-country Pacific sardine fishery game theoretic model accounting for changes in the distribution and abundance of the Pacific sardine stock in response to ocean climate variability is simulated under six ocean climate variability scenarios with seven possible coalition

structures made up for Canada, the U.S. and Mexico. The stand-alone stability of coalition structures was analyzed using group and individual rationality criteria.

Given various ocean climate variability scenarios, the imperative question now is how can stable economically feasible sharing rules for the Pacific sardine resource be shared under various possible ocean climate variability scenarios. One approach that appears promising is to provide for, and encourage, side payments to prevent countries from behaving as free-riders, and make the grand coalition stand-alone stable. Our results suggest that this might be accomplished through a system of dynamic transferable catch share between countries so that full utilization of the optimal catch is achievable.

We believe that if the catch of each country is restricted by the fish availability of the Pacific sardine resource within its waters as determined by ocean climate variability, transferability of economic rents from the resource is capable of generating is one key element to achieve stable cooperative transboundary management. While possible disagreements over sharing economic benefits would not be eliminated, ongoing efforts to enhance scientific understanding of the relationship between ocean climate variability in the CCE and the abundance and distribution of

Pacific sardine would further foster efforts to cooperatively manage the Pacific sardine resources by Mexico, the U.S. and Canada.

Table 3-1 Characteristic functions and the probability that the biomass falls below 10% of the initial biomass (1.2 million tonnes) at least once over the 35-year trajectory ($B < 10$) for (a) time-increment SST and (b) time-decrement SST scenarios. Bold numbers indicate payoffs for free-ridings. Bolded coalitions indicate to have stand-alone stability. Note that the average total payoffs slightly differ from the sum of the three countries' due to rounding.

(a-1) Payoffs (present net benefits: million USD) in time-increment SST scenario ($\mu = + 0.044$).

Coalition	Free-rider	CA	US	MX	Coalition payoff	Total payoff	$B_{<10}(\%)$
{CA,US,MX}d		181	191	89	461	461	0.0
{CA,US,MX}f		61	322	40	424	424	0.0
{CA,U.S}	{MX}	156	105	175	261	436	1.0
{US,MX}	{CA}	253	94	74	169	422	2.5
{CA}{US}{MX}		152	68	108		327	43.4

(a-2) Payoffs (present net benefits: million USD) in time-increment SST scenario ($\mu = + 0.088$).

Coalition	Free-rider	CA	US	MX	Coalition pay off	Total payoff	$B_{<10}(\%)$
{CA,US,MX}d		231	176	62	469	469	0.0
{CA,US,MX}f		83	306	28	417	417	0.0
{CA,U.S}	{MX}	203	96	147	299	446	0.9
{US,MX}	{CA}	283	92	50	142	425	2.2
{CA}{US}{MX}		175	67	92		333	39.9

(a-3) payoffs (present net benefits: million USD) in time-increment SST scenario ($\mu = + 0.132$).

Coalition	Free-rider	CA	US	MX	Coalition pay off	Total payoff	$B_{<10}(\%)$
{CA,US,MX}d		280	156	41	477	477	0.0
{CA,US,MX}f		109	276	19	404	404	0.0
{CA,U.S}	{MX}	257	85	116	342	458	0.5
{US,MX}	{CA}	313	85	31	117	429	2.1
{CA}{US}{MX}		201	63	77		341	34.5

(b-1) payoffs (present net benefits: million USD) in time-decrement SST scenario ($\mu = - 0.044$).

Coalition	Free-rider	CA	US	MX	Coalition pay off	Total payoff	$B_{<10}(\%)$
{CA,US,MX}d		89	185	170	444	444	0.0
{CA,US,MX}f		29	306	80	415	415	0.0
{CA,U.S}	{MX}	76	104	234	181	415	1.4
{US,MX}	{CA}	182	88	145	234	416	2.0
{CA}{US}{MX}		107	66	149		321	42.1

(b-2) payoffs (present net benefits: million USD) in time-decrement SST scenario ($\mu = - 0.088$).

Coalition	Free-rider	CA	US	MX	Coalition pay off	Total payoff	$B_{<10}(\%)$
{CA,US,MX}d		58	167	210	435	435	0.0
{CA,US,MX}f		19	278	104	400	400	0.0
{CA,U.S}	{MX}	47	97	260	144	403	1.5
{US,MX}	{CA}	149	79	185	264	413	1.2
{CA}{US}{MX}		88	63	171		321	35.6

(b-3) payoffs (present net benefits: million USD) in time-decrement SST scenario ($\mu = - 0.132$).

Coalition	Free-rider	CA	US	MX	Coalition pay off	Total payoff	$B_{<10}(\%)$
{CA,US,MX}d		38	144	246	428	428	0.0
{CA,US,MX}f		12	241	129	383	383	0.1
{CA,U.S}	{MX}	28	86	281	114	395	1.2
{US,MX}	{CA}	115	69	224	294	408	0.8
{CA}{US}{MX}		71	60	193		323	30.5

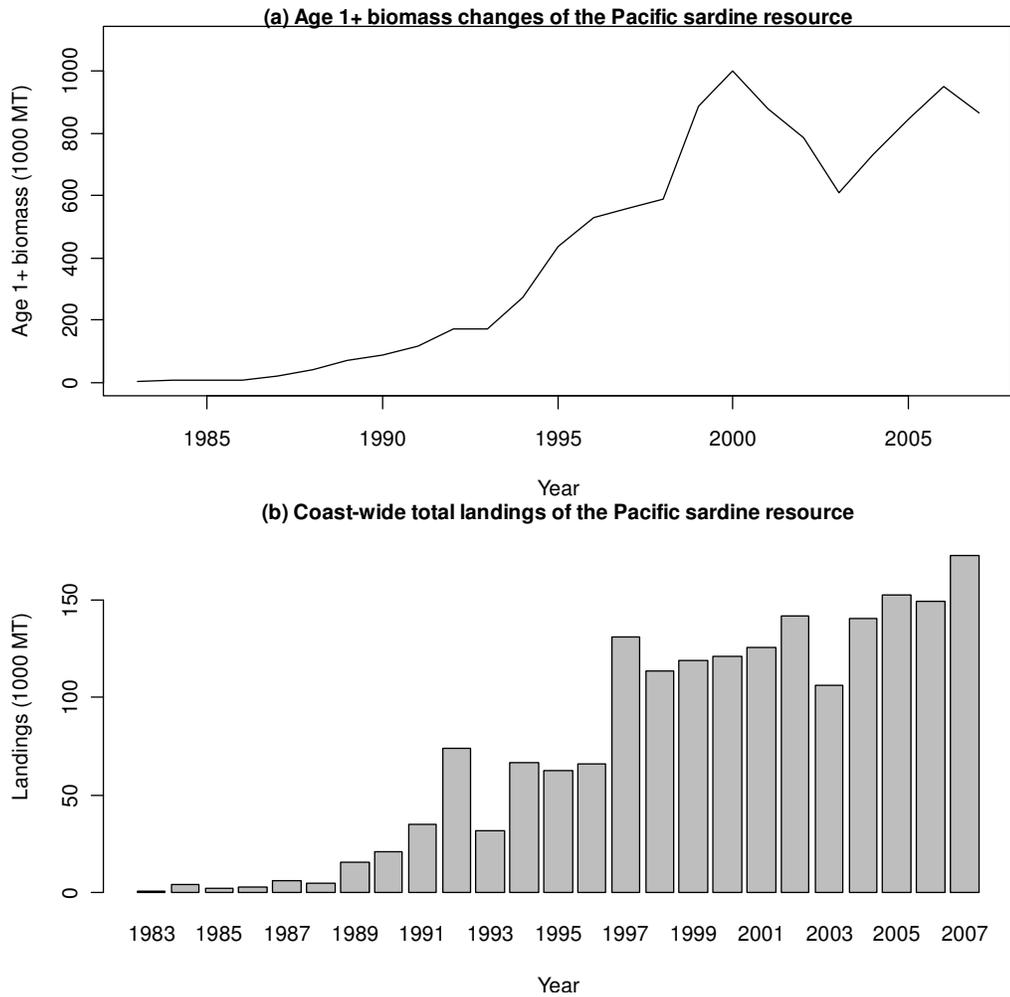


Figure 3-1 (a) Age 1+ biomass change of the Pacific sardine resource between 1983 and 2007. (b) Coast-wide landings of the Pacific sardine resource between 1983 and 2007 (date from Hill *et al.*, 2009).

Chapter 3 references

Aguero, M., and E. Gonzalez. 1996. Transboundary Stocks of Small Pelagic Fish: Problems and Options, World Bank Discussion Paper No. 329, Fisheries Series, Washington.

Armstrong, C. W., and U. R. Sumaila. 2001. Optimal allocation of TAC and the implications of implementing an ITQ management system for the north-east arctic cod. *Land Economics* 77(3):350-59.

Alheit, J., and E. Hagen. 1997. Long-term climate forcing of European herring and sardine populations. *Fisheries Oceanography*. 6(2): 130-139.

Bakun, A. 1998. Ocean triads and radical interdecadal variation: Bane and boon to scientific fisheries management. In: T. J. Pitcher, P. J. B. Hart and D. Pauly (eds.), *Reinventing Fisheries Management*, Chapman & Hall, London, 331–358.

Brander, K.M. 2007. Global fish production and climate change. *Proceeding of National Academy of Science* 104(50): 19709-19714.

Brandt, U. S., and L. G. Kronbak. 2010. On the stability of fishery agreements under exogenous change: An example of agreements under climate change. *Fisheries Research* 101: 11-19.

Emmett, R. L., R. D. Brodeur, T. W. Miller, S. S. Pool, G. K. Krutzikowsky, P. J. Bentley, and J. McCrae. 2005. Pacific sardine (*Sardinops sagax*) abundance, distribution, and ecological relationships in the Pacific Northwest. *Reports of California Cooperative Oceanic Fisheries Investigations* 46:122.

Fox, W. W. 1970. An exponential yield model for optimizing exploited fish populations. *Transactions of the American Fisheries Society* 99:80-88.

Hannesson, R. 2005. Global warming and fish migrations. *Institute for Research in Economics and Business Administration Report* N01/05.

Hannesson, R., 2006a. Sharing Fish: Norwegian spring-spawning herring, in Hannesson, R., M. Barange and S. Herrick, (ed.) *Climate change and the economic of the world's fisheries*, Edward Elgar Publishing, Northampton.

Hannesson, R., 2006b. Individual rationality and the 'zonal attachment' principle: Three stock migration models. *Environmental Resource Economics* 34(2): 229-245.

Hannesson, R., S. Herrick. and J. Field. 2009. Ecological and economic consideration in the conservation and management of the Pacific sardine (*Sardinops sagax*). *Canadian Journal of Fisheries and Aquatic Science* 66(5): 859-868.

Herrick, S., J. Norton, J.E. Mason, and C. Bessey. 2007. Management application of an empirical model of sardine-climate regime shifts. *Marine Policy* 31(1): 71-80.

Hill, K. T., N. C. H. Lo, B. J. Macewicz and R. Felix-Uraga. 2007. Assessment of the Pacific sardine (*Sardinops sagax caerulea*) population for U.S. management in 2006. *NOAA Technical Memo. NOAA-TM-NMFS-SWFSC-386*. 75p.

Hill, K. T., N. C. H. Lo, B. J. Macewicz and R. Felix-Uraga. 2009. Assessment of the Pacific sardine resources in 2008 for U.S. management in 2008. *forthcoming* as NOAA Technical Memo.

Ishimura, G., U.R. Sumaila, and S. Herrick. 2010. Fishing games under climate variability: Transboundary Management of Pacific sardine in the California Current Ecosystem. *Fisheries Center Working Paper # 2010-1*, The University of British Columbia, Vancouver, B.C., Canada.

Jacobson, L.D., and A.D. MacCall. 1995. Stock-recruitment models for pacific sardine (*Sardinops sagax*). *Canadian Journal of Aquatic and Fisheries Sciences* 52(3): 566-577.

Jacobson, L.D., S.J., Bograd, R.H. Parrish, R. Mendelssohn, and F.B. Schwing. 2005. An ecosystem-based hypothesis for climatic effects on surplus production in California sardine (*Sardinops sagax*) and environmentally dependent surplus production models. *Canadian Journal of Aquatic and Fisheries Sciences* 62(8): 1782-1796.

Kaitala, V., and M. Lindroos. 1998. Sharing the benefits of cooperation in high seas fisheries: A characteristic function game approach. *Natural Resource Modeling* 11(4):275-99.

Kronbak, L. G., and M. Lindroos. 2006. An enforcement-coalition model: Fishermen and authorities forming coalitions. *Environmental and Resource Economics* 35(3):169-194.

Kronbak, L. G., and M. Lindroos. 2007. Sharing rules and stability in coalition games with externalities. *Marine Resource Economics* 22(2):137-154.

- Laukkanen, M. 2003. Cooperative and non-cooperative harvesting in a stochastic sequential fishery. *Journal of Environment Economics and Management* 45(2): 454-473.
- Li, E. 1998. Cooperative high-seas straddling stock agreement as a characteristic function game. *Marine Resource Economics* 13(4):247-58.
- Lindroos, M. 2004a. Restricted coalitions in the management of regional fisheries organizations. *Natural Resource Modeling* 17(1):45-69.
- Lindroos, M. 2004b. Sharing the benefits of cooperation in the Norwegian spring-spawning herring fishery. *International Game Theory Review* 6(1):35-53.
- Lindroos, M., and V. Kaitala. 2000. Nash equilibrium in a coalition game of the Norwegian spring-spawning herring fishery. *Marine Resource Economics* 15(4):321-39.
- McKelvey, R., P. Golubtsov, K. Miller, and G. Crip. 2006. Bi-national management of a transboundary marine fishery: modelling the destabilizing impacts of erratic climate shifts, in Hannesson, R., M. Barange, and S. Herrick (ed.) *Climate change and the economic of the world's fisheries*, Edward Elgar Publishing, Northampton.
- MacCall, A. D. 1976. Density dependence of catchability coefficient in the California Pacific sardine, *Sardinops sagax caerulea*, purse seine fishery. *California Cooperative Fisheries Investigations Reports*, 18: 136-148.
- MacCall, A. D. 1990. *Dynamic geography of marine fish populations*. University of Washington Press, Seattle USA.
- Miller, K.A. 2007. Climate variability and tropical tuna: Management challenges for highly migratory fish stocks. *Marine Policy* 31(1): 56-70.
- Miller, K.A., and G.R. Munro. 2004. Climate and cooperation: A new perspective on the management of shared fish stocks. *Marine Resource Economics* 19(3): 367-393.
- Munro, G.R. 1979. The optimal management of transboundary renewable resources. *Canadian Journal of Economics* 12(3):355-76.

- Munro, G.R. 1990. The optimal management of transboundary fisheries: Game theoretic considerations. *Natural Resource Modeling* 4(4):403-26.
- Munro, G.R. 2002. The optimal management of transboundary renewable resources. *Fisheries Economics: Collected Essays Vol.2*: 63-84. Ashgate Publication Ltd, UK.
- Munro, G.R., A. Houtte, and R. Willmann. 2004. The conservation and management of shared fish stocks: Legal and economic aspects. FAO Fisheries Technical Paper, Rome Italy.
- Nash, J. 1953. Two-person Cooperative Games, *Econometrica* 21 (1953), 128–140.
- Perry, A.L., P.J. Low, J.R. Ellis, and J.D. Reynolds. 2005. Climate change and distribution shifts in marine fishes. *Science*. 308 (5730): 1912-1915.
- Pintassilgo, P. 2003. A coalition approach to the management of high seas fisheries in the presence of externalities. *Natural Resource Modeling* 16(2): 175-197.
- Pintassilgo, P., and Lindroos, M. 2008. Coalition formation in straddling stock fisheries: A partition function approach. *International Game Theory Review* 10(3): 303-317.
- Radovich, J. 1973. A challenge of accepted concepts involving catch per unit effort data. *Proceedings of the Annual Meeting of the California-Nevada Chapter of the American Fisheries Society*, 6 pp.
- Radovich, J. 1976. Catch-per-unit-of-effort: fact, fiction or dogma. *California Cooperative Fisheries Investigations Reports*, 18: 31-33.
- Radovich, J. 1981. The collapse of the California sardine fishery: what have we learned?, in M. H. Glantz and J. D. Thompson (eds), *Resource Management and Environmental Uncertainty*, New York, US: John Wiley & Sons.
- Rodriguez-Sanchez, R., D. Lluch-Belda, H. Villalobos, and S. Ortega-Garcia. 2002. Dynamic geography of small pelagic fish populations in the California current ecosystem on the regime time scale. *Canadian Journal of Fisheries and Aquatic Sciences* 59(12):1980-1988.

Sumaila, U. R. 1995. Irreversible capital investment in a two-stage bimatrix fishery game model. *Marine Resource Economics* 10(3):263-83.

Sumaila, U. R. 1999. A review of game theoretic models of fishing. *Marine Policy* 23(1):1-10.

United Nations, 1982. United National Convention on the Law of the Sea. UN Doc. A/Conf. 62/122.

Wolf, P. 1992. Recovery of the Pacific sardine and the California sardine fishery. *Reports of California Cooperative Oceanic Fisheries Investigations* 33:76-86.

Yi, S. 1997. Stable coalition structures with externalities. *Games and Economic Behavior* 20(2): 201-237.

**CHAPTER 4. THE COST OF DELAYING COOPERATIVE MANAGEMENT OF A
TRANSBOUNDARY FISH STOCK VULNERABLE TO CLIMATE VARIABILITY: THE
CASE OF PACIFIC SARDINE¹⁰**

¹⁰ A version of this chapter has been submitted for publication. Ishimura, G. U.R. Sumaila and S. Herrick (2010) The cost of delaying cooperative management of a transboundary fish stock vulnerable to climate variability: the case of Pacific sardine.

4.1 Introduction

Ocean climate variability, on both inter-annual and decadal scales, alters the marine environment over time (Brander 2007). Impacts that can result through such changes in the marine environment include food availability and the habitats for marine organisms. Fish stocks often respond to these changes by 1) increasing or reducing their abundance; and 2) migrating to habitats conducive for growth and reproduction. These two responses are not mutually exclusive, and jointly result in changes in the local fish availability, thus inevitably threatening the spatial stability of available fish stocks for fisheries exploitation.

This issue of spatial instability is a critical challenge particularly with a transboundary fish stock which is exclusively shared by more than one country. Without cooperative agreements, competing fishing activities, upon which the impacts of ocean climate variability could have compounding effects, threaten transboundary fish stocks. Two critical elements to fisheries management need to be agreed on for there to be cooperation in the use of a transboundary fish stock (Munro *et al.*, 2004). First, the size of the fish stock left unfished, called the escapement biomass, must be agreed upon to ensure the resource's sustainability. The escapement biomass thus defines the total allowable catch (TAC) permitted to participating fishing countries. Second, the allocated share of the total catch permitted to each country needs to be addressed. Fixed shares of catch have often been allotted by considering the catch history of the countries

involved, fixed physical distribution of stocks, or the migration patterns of a transboundary fish stock. With spatial instability of a fish stock caused by ocean climate variability, fixed allocations may no longer be effective, and therefore, it is anticipated that challenges to establishing cooperative transboundary management will arise.

Potential uncertainties in fisheries production and spatial distribution arising from ocean climate variability have received increasing attention in transboundary fishery management over the years. A body of scientific studies on the impacts of ocean climate variability on a fishery has quickly developed, but it is mostly limited to geographical considerations or methodological approaches rather than by anticipating effects on a fish stock or fisheries (Brander 2009). In terms of practical case studies on transboundary fish stocks under climate variability, Laukkanen (2003) devised a multinational fishing game for Northern Baltic salmon with environmental variability in recruitment, and concluded that there were significant effects from environmental variability on maintaining cooperative management. Miller and Munro (2004) undertook a case study of Canada - US Pacific salmon fishery management in which abundance and distribution changes related to ocean climate variability are taken into account, and concluded that predictions of the impacts of environmental variability on a fish stock are a key to successful cooperative managements. Miller (2007) argued that the stability of regional

fishery management organizations for highly migratory fish stocks¹¹ (e.g., tropical tuna) is heavily dependent on how effectively countries' incentives for cooperative management are maintained under the anticipated changes to fish stocks by ocean climate variability. Despite these three studies successfully demonstrating the need for cooperative management of transboundary fish stocks under ocean climate variability, studies that estimate the risk of overexploitation and the loss of potential economic benefits, from a transboundary fish stock under ocean climate variability and non-cooperative management, are largely absent from the academic literature.

A large challenge in the management of a transboundary fish stock, where its availability is affected by ocean climate variability, lies in delaying implementation of cooperative management and consequently incurring the cost of such delays. First, it takes a long time to recognize and confirm changes in a fish stock caused by ocean climate variability, to which must be added the time needed to predict anticipated changes. Second, negotiations to establish cooperative management take additional time because of likely conflicts in economic interests compounded by political obstructions. Such negotiations also include agreements on anticipated changes to a fish stock and decisions on sharing future benefits among the participating

¹¹ A highly migratory fish stock is one type of shared fish stocks that migrate through both exclusive economic zones and the high seas. While a transboundary fish stock can be exclusively fished by participating countries, in principal, highly migratory fish stocks can be fished freely on the high seas by any country.

stakeholders on both the domestic and international levels. These difficulties all serve to delay the adoption of cooperative management of a transboundary fish stock.

As in Miller (2007), one key to the stability of cooperative management of a transboundary fish stock is to maintain the participating countries' incentives to continue to cooperate, despite changes in fish abundance and distribution. Therefore, revealing the cost of delaying such cooperative management, which includes both the potential loss of economic benefits and the risk of stock depletion, would help give countries sufficient incentives to engage in cooperative exploitation to avoid potential negative outcomes. Although the number of global studies on the cost of adapting to climate changes is rapidly increasing (e.g., World Bank 2009), as far as we know, studies on the cost of delaying cooperative management on a transboundary fish stock under ocean climate variability have been largely absent until now.

Transboundary fishery management of Pacific sardine (*Sardinops sagax*) in the California Current Ecosystem (CCE) is now faced with the aforementioned challenges, under ocean climate variability. Inter-annual and decadal scale climate variability, with drivers such as the El Niño/Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO), has shaped the ocean climate of the CCE, which extends up to southern Vancouver Island from Baja

California (Field and Francis 2002). Since the early twentieth century, three ocean climate regime shifts have been recognized; a warm regime from 1925 to 1947, a cold regime between the 1940s and late 1970s, and a warm regime from 1977 to the present (Figure 4-1) (McFarlane *et al.*, 2000).

While projecting trajectories of ocean climate variability in the CCE and the subsequent dynamics of Pacific sardine is in the early stages, the need to establish a robust cooperative management by Mexico, the U.S. and Canada seems pressing. However, currently, no cooperative management exists. Accepting cooperative exploitation will require strong economic incentives and the threat of a collapse of the fish resource. Therefore, creating incentives for the three countries to engage in cooperative management of Pacific sardine is an urgent need if we are to minimize the risk of the degradation of economic benefits and depletion of the Pacific sardine stock.

To this end, this study aims to reveal the cost of delaying cooperative exploitation of the Pacific sardine fish stock under ocean climate variability. Ishimura *et al.* (2010) developed a three-country transboundary fishery bioeconomic model for Pacific sardine incorporating distribution and abundance uncertainties under CCE ocean climate variability. They showed the potential

effects on economic and biological outcomes from cooperative and non-cooperative management of the Pacific sardine stock by the three countries rather than precise estimations of biomass and economic outcomes. This study further extends their model to estimate the cost and the risk of depletion to a fish stock, in this case Pacific sardine, from delays in cooperative exploitations. In the study, we conduct 35-year simulations, and define the ‘cost of delay’ as the difference in net economic benefits between a) cooperative management by the three countries for all 35 years, and b) cooperative management after i years of non-cooperative management. We summarize and discuss the results from the simulations.

4.2 Material and methods

4.2.1 Pacific sardine in the California Current Ecosystem

The abundance and distribution of the northern stock¹² of Pacific sardine, which is the largest substock in the CCE that is exclusively fished by Canada, the U.S. and Mexico, has exhibited extreme variations as result of three regime shifts in the CCE (Norton *et al.*, 2005; Herrick *et al.*, 2007). In this study, hereafter, the term Pacific sardine implies this northern stock. Until the early 1940s under a warm regime, the biomass of Pacific sardine varied between 1.2 million and 2.8 million tonnes, and sardine fisheries were widespread in Canada, the U.S. and Mexico.

¹² Three substocks of Pacific sardine in the CCE (Felix-Uraga *et al.* 2005a; 2005b) are widely recognized. These are the 1) northern substock, which is found from northern Baja California to south-eastern Alaska; 2) southern substock whose distribution ranges from Baja California to southern California; and 3) Gulf of California substock, which spends its life within the Gulf of California.

Between the late 1940s and 1970s a cold regime shift in the CCE, combined with overfishing, resulted in the collapse of the Pacific sardine stock, with biomass falling below 5,000 tonnes. As abundance decreased, the spatial availability for commercial fisheries shifted from a wide range to the limited southern region of southern California and Mexico. Finally, directed fisheries for Pacific sardine in the U.S. were closed in 1974 (Wolf 1992). In the 1980s, a warm regime shift occurred in the California Current, and coupled with conservation efforts, the abundance of Pacific sardine rebounded to 1940s levels, and reappeared in the waters of the Northwest U.S. (Oregon and Washington) and Canada. In 1986, directed fisheries for Pacific sardine officially reopened in the U.S. Canada removed Pacific sardine from its endangered species list and reopened its sardine fisheries in 2003. In 2006, the estimated biomass of Pacific sardine reached 1.2 million tonnes. In 2008, the estimated biomass decreased to 0.58 million tonnes (Hill *et al.*, 2009). Latest improvements to the stock assessment model have resulted in a retrospective reduction in biomass estimates for recent years (see Hill *et al.*, 2007, 2008, 2009). Currently, although unconfirmed, we are likely facing a cold regime shift in the CCE. In summary, warm regimes enhance the abundance of Pacific sardine and expand its distribution. Cold regimes lessen abundance and restrict distribution.

4.2.2 Model overview

Our integrated model mimics ocean climate variability in the CCE and the abundance and distribution of Pacific sardine stocks corresponding to ocean climate variability. Previous studies have demonstrated significant correlations between sea surface temperature (SST), abundance, and distribution of Pacific sardine¹³ (e.g. Herrick *et al.*, 2007; Jacobson and MacCall 1995; Jacobson *et al.*, 2005). This study therefore assumes that SST is a major driver of biomass abundance and the geographical distribution of Pacific sardine, and adapts the model developed by Ishimura *et al.* (2010). Our alternative stochastic model consists of four components: *a*) a population dynamics model driven by SST; *b*) a biomass distribution model spread over three countries; *c*) an SST development model; and *d*) an information model of fish stock distribution. We integrate these four components to model the expected population dynamics and distribution of Pacific sardine.

4.2.3 Population dynamics model driven by SST

We adapt a surplus production model with environmentally dependent components developed by Jacobson *et al.* (2005), and assume that the fish stock migrates from a spawning area to each country's fishing grounds and then returns to their spawning ground for reproduction. Fishing is assumed to occur after reproduction, and occurs simultaneously in each country's fishery. From

¹³ SST at the Scripps Institute of Oceanography pier, in La Jolla, California (SIO SST), is often used as an indicator of the decadal cold-warm shifts in the CCE.

the Gompertz-Fox model (Fox 1970), Jacobson *et al.* (2005) calculated environmentally dependent surplus production as:

$$4-1 \quad B_{y+1} = S_y - e\eta S_y \ln \left(\gamma \frac{S_y}{I_y} \right)$$

$$4-2 \quad S_y = B_y - h_y^{Canada} - h_y^{U.S.} - h_y^{Mexico}$$

where B_y and S_y are the biomass and escapement biomass at year y , respectively. The constant e is Euler's number (2.718), I_y is SST at year y , which affects the stock's carrying capacity. η and γ are constants. For the Gompertz-Fox model, η is the ratio of the maximum productivity and the carrying capacity (Quinn and Deriso 1999). The constant γ is a scaling factor for SST to the carrying capacity. Ishimura *et al.* (2010) estimated η (0.04) and γ (2.55) by using updated stock assessment data from Hill *et al.* (2007). This study incorporates these estimations.

4.2.4 Objective function under cooperative management

Here, we assume that the three countries fish cooperatively thereby acting as the sole owner of the fish stock and seek to maximize joint benefits by adjusting the optimal escapement biomass, S_y^* . The objective function that maximizes the present value of the economic benefit at year y ($f_{solo,y}$) is assumed to be:

$$4-3 \quad \max \quad f_{solo,y}(S_y^*) = p \cdot (B_y - S_y^*) + \frac{d \cdot p \cdot \left\{ -e\eta S_y^* \ln \left(\gamma \frac{S_y^*}{I_y} \right) \right\}}{1-d}$$

$$\text{where } d = \frac{1}{1+r}$$

where d is the discount factor and r is the discount rate. We assume a constant net economic price per unit catch ($p= 0.03$ USD per pound). The first term expresses the economic benefits from the current catch and the second term expresses the future economic benefit (Hannesson 2005). In this study uses a discount rate, 5% to project economic and biological outcomes. With rates of 3%, 10% and 15% applied to assess the sensitivity of the model to different discounting rates. For the maximization of the objective function under sole ownership (cooperative management), the optimal escapement biomass (S_y^*) is calculated using the first order condition of Equation 4-3:

$$4-4 \quad S_{solo,y}^* = \frac{I_y}{\gamma} e^{-\left(1+\frac{1-d}{d\eta}\right)}$$

4.2.5 Objective function under non-cooperative management

Hannesson (2005, 2006) studied a transboundary fish stock that migrates between two countries with time-variant distribution changes under climate change. Two complementary assumptions related to the maximization problem are assumed in his study. First, the minor country, with less than a half share (distribution) of a fish stock, has an incentive to fish the biomass level

down to zero ($S^{Minor*} = 0$). Second, the major country with more than half the share (distribution) of a fish stock has an incentive to leave the stock in the ocean until it reaches the level that maximizes net present value of the benefits. This paper adopts this variant major/minor framework and develops an optimal escapement biomass for non-cooperative management based on the updated Jacobson's population dynamics model by Ishimura *et al.* (2010). The escapement biomass that maximize discounted present value for invariant shares of a fish stock are:

$$4-5 \quad \begin{cases} S_{w,y}^{Major*} = \frac{I_y}{\gamma} e^{-\left(\frac{1-d}{d\eta\hat{D}_{w,y}}+1\right)} & \text{if } \hat{D}_{w,y} > 0.5 \\ S_{w,y}^{Minor*} = 0 & \text{Otherwise} \end{cases}$$

where \hat{D} is the expected distribution of a fish stock. Hanneson's analysis was for a two-agent model, where a fish stock's distribution clearly defined which country is major and minor except when the two countries' distributions were the same ($\hat{D}=0.5$) and the two countries jointly acted as the sole owner. In our three-agent model with Canada, the U.S. and Mexico, however, it is possible for the biomass distributions of all countries to be less than 0.5, in which case all countries act as minor players. This could lead to the drastic depletion of Pacific sardine.

4.2.6 Sea surface temperature development model

The nature of the climate regime of the CCE is based on decadal scale interchanges of warm and cold regime shifts (two or three regime shifts during the twentieth century). This study adopts a 35-year time trajectory where one regime shift from warm to cold and vice versa, would be appropriate. We use an increasing and a decreasing trend of SST (τ), calculated as:

$$4-6 \quad \tau_{y+1} = \tau_y + \mu + \sigma \Delta z_y$$
$$\Delta z_y \sim N(0,1)$$

where y is year. Equation 4-6 generates a stochastic SST trend as the sum of two components:

1) a static driven part, μ ; and 2) a stochastic error term, Δz_y . In this study, the value for μ and σ are 0.044 and 0.602, respectively, obtained from the average annual SIO SST from 1970 to 2002, which is considered a warm regime period in the CCE (from Ishimura *et al.*, 2010). The current situation in the CCE might be the initial stage of a cold regime shift, but this is yet to be confirmed since it takes several years to confirm warm and cold climate regimes. Therefore, the period from 1970 to 2002, which has been confirmed as a warm climate regime is the period which we use as a basis to estimate ocean climate variability. This study evaluates two scenarios for SST trends, 1) an increasing (time-increment) SST trend ($\mu = 0.044$); and 2) a decreasing (time-decrement) SST trend ($\mu = -0.044$). The estimated SST (τ_y) from Equation 4-6 now replaces I in Equations 4-4 and 5.

4.2.7 Biomass distribution model driven by SST

The biomass distribution model of Pacific sardine is a discrete three-box model. With changes in SST, the sardine biomass is redistributed between Mexico (*MX*), the U.S. (*US*) and Canada (*CA*) in a discrete manner. The general pattern of the distribution of Pacific sardine within country w (D_w) relative to the others is assumed to be linear when the SST (τ) drops below the low threshold level (τ_{low}), and then approaches zero ($D_w = 0$) as the high threshold level of SST (τ_{high}) is reached.

$$4-7 \quad \left\{ \begin{array}{l} D_{MX,y} = \min \left[1, (\tau_{high_{MX}} - \tau_y) / (\tau_{high_{MX}} - \tau_{low_{MX}}) \right] \\ D_{US,y} = (1 - D_{MX,y}) \cdot \min \left[1, (\tau_{high_{US}} - \tau_y) / (\tau_{high_{US}} - \tau_{low_{US}}) \right] \\ D_{CA,y} = 1 - D_{MX,y} - D_{US,y} \end{array} \right.$$

$$\text{s.t. } 0 \leq D_{w,y} \leq 1$$

$$D_{MX,y} + D_{US,y} + D_{CA,y} = 1$$

This study models biomass distribution by estimating a direct relationship between SST and discrete biomass distributions over the Exclusive Economic Zones (EEZs) of Mexico, the U.S. and Canada based on three descriptive facts. First, the current U.S. harvest policy for Pacific sardine assumes a fixed distribution with 87 % of the northern stock in U.S. waters (California,

Oregon and Washington) and 13 % in Mexican waters (Pacific Fishery Management Council 1998), and does not include a percentage for Canada (Hill *et al.*, 2008). Second, Canadian management assumes a fixed biomass distribution where 10% of the northern stock is assumed to enter Canadian waters. This assumption is based on an analysis of historical catch and trawl survey data (DFO 2004). Third, around 1990, Pacific sardine reappeared in Canadian waters. Based on the above observations and analyses, this study makes two assumptions about the relationship between SST and the biomass distribution of Pacific sardine. First, at an SST of 17.9 °C, which was the five-year average SIO SST in 1999, the proportions of the biomass of Pacific sardine in Mexico, the U.S. and Canada are set at 13%, 78% and 9%, respectively. Second, at a SST of 17.5 °C, which was the five-year average in 1992, the proportions of the biomass of Pacific sardine in Mexico, the U.S. and Canada are 20%, 77% and 3%, respectively. We set different high and low threshold levels for Mexico ($\tau_{high_{MX}} = 18.3$ and $\tau_{low_{MX}} = 15$) and the U.S. ($\tau_{high_{US}} = 21.5$ and $\tau_{low_{US}} = 17.5$), with Canada having the residuals.

Since our intention in this study is not the precise estimation of biomass or economic outcomes, but rather to examine the effects of delaying cooperative management, we use five-year averages from 1997 and 2001, a confirmed warm regime of the CCE, as the initial SST, 17.9° C, and initial biomass, 1.2 million tones, in the simulations (Hill *et al.*, 2007). The initial biomass

distributions for Mexico, the U.S. and Canada are set at 13%, 78%, and 9%, respectively. As SST reaches 19.4 °C, more than half the biomass is distributed in Canadian waters¹⁴. More than half the biomass is distributed in Mexican waters when the SST drops below 16.7 °C (Figure 4-2).

4.2.8 Information model for biomass distribution

We incorporate an auto-correlation function into the estimation of expected fish share for each country based on the assumption that changes in the biomass distribution of Pacific sardine is based on existing and past time series of biomass distributions. Therefore, a time dependent auto-correlated error function is appropriate. This is expressed as:

$$4-8 \quad \hat{D}_{w,y} = \rho \cdot D_{w,y} + (1 - \rho) \hat{D}_{w,y-1}$$

$$\text{s.t. } 0 \leq \hat{D}_{w,y} \leq 1$$

$$\hat{D}_{w,0} = D_{w,0}$$

¹⁴ The historical maximum and minimum SIO between 1918 and 2002 was 19.1°C in 1997 and 15.5 in 1975, respectively.

where $\hat{D}_{w,y}$ is an expected distribution at time y in country w , and ρ is the auto-correlation weighting factor. The value of the weighting factor (ρ) captures the information delay regarding a fish stock's distribution. The magnitude of the weighting factor affects the amount of the stock, expects to have availability to update their fishing strategy. In the simulations, we assume symmetric information for the three countries and arbitrarily set the weighting factor at $\rho = 0.5$. Sensitivity analysis was carried out in Ishimura *et al.* (2010).

4.2.9 Catch

Due to the time-variant fish stock distribution and information delays, the target catch might be more than the amount of fish available in each country's waters. The catch in a given year for each country is expressed as:

$$4-9 \quad h_{w,y} = \min \{ D_{w,y} \cdot B_y, \hat{h}_{w,y} \}$$

$$\text{where } \hat{h}_{w,y} = \hat{D}_{w,y} \cdot B_y - S_{w,y}^*$$

where the target catch (\hat{h}) is induced by the expected distribution (\hat{D}), biomass (B) and the optimal escapement biomass (S) at year y .

4.2.10 Cost of delaying cooperative management

The present value (PV) of the net economic benefits from fishing by the three countries over the 35-year time horizon of the 10,000 simulations is taken as the measure of economic performance. The average of the present value of benefits received by each country is calculated as:

$$4-10 \quad \overline{PV}_w = \frac{1}{10,000} \sum_{k=1}^{10,000} PV_w^k$$

where PV_w^k is the net present value for country, w , in the k^{th} simulation:

$$4-11 \quad PV_w^k = \sum_{y=1}^{35} d^{y-1} \cdot \pi_{w,y}^k$$

We define the i^{th} year delay of cooperative management in the 35-year projection as:

- 1) From the first to i^{th} year, all countries engage in non-cooperative management,
- 2) From $i^{\text{th}} + 1$ year to 35th year, all countries engage in cooperative management.

The cost of delaying cooperative management for a country, w , ($C_{w,i}$) is assumed to be the difference between the present value of benefits under cooperative management over the entire 35-year period and the i^{th} -year delay in non-cooperative management.

$$4-12 \quad C_{w,i} = \overline{PV}_{w,35} - \overline{PV}_{w,i}$$

The 35-year time horizon is assumed as the management time horizon in this study. The total cost to the three countries is defined as the sum of the individual cost to the three countries:

$$4-13 \quad C_{Total,i} = C_{Canada,i} + C_{U.S.,i} + C_{Mexico,i}$$

This is a generalization of many earlier results of game theoretic models of fishing, where the difference in net benefits under cooperative and non-cooperative management (i.e., the loss due to non-cooperation throughout the time horizon of the analysis) are expected to motivate cooperation (e.g., Sumaila, 1997).

4.2.11 Biological indicators - the conservation risk

We assume that the conservation risk, or the probability that the biomass falls below 10 % of the initial biomass (1.2 million tonnes), happens at least once over the 35-year time horizon. Ten

percent was chosen because of the biological resilience of Pacific sardine is high as shown by its history (less than 5,000 tonnes of a Pacific sardine during 1970s).

$$4-14 \quad P(B_y^k < 0.1B_0) = \frac{1}{10,000} \sum_{k=1}^{10,000} I(B_y^k < 0.1B_0)$$

where $I(B_y^k < \varphi B_0)$ is an indicator that equals 1 if the biomass during year y in simulation k is less than φ (0.1) of the initial biomass.

4.3 Results

The results of costs of delaying cooperative management with a discount rate of 0.05 are presented in Tables 4-1 and 4-2, respectively. Since a zero-year delay in cooperative management implies cooperative exploitation for all years, the cost for the zero-year delay is zero. The 35th-year delay implies that all countries are engaged in non-cooperative management through all years. The maximum total cost of 88.1 million USD occurred at the 25th-year of delay (Table 4-1) for the time-increment SST scenario, and 80.6 million USD for the time-decrement SST scenario (Table 4-2); the costs of delaying cooperative management then decreased beyond the 25th-year of delay. The total cost for the time-increment and decrement SST scenario showed a ‘concave’ trend. This implies that cooperative management should not

be attempted if the expected delay in implementing cooperative management were to exceed 25 years. This is because the total cost of delay is the sum of all the three countries' costs, the significantly high cost for the U.S. offsets the economic benefits of engaging in non-cooperative behavior for Canada and Mexico. With more delay in cooperative management, 1) there is less benefit from fewer years of cooperative management; and 2) the cost to rebuild to the optimal escapement biomass from a depleted stock level would result in high conservation risks in later years (see Table 4-3 and 4-4). With combinations of these elements, a 'concave' type trend appeared. It is, however, certain that the delay in cooperative exploitation increases the conservation risk proportional to the years of delay, for all discount rates and both ocean climate scenarios (Table 4-3 and 4-4).

In both ocean climate scenarios, the most distinguishing feature is the significant costs for the U.S (Table 4-1 and 4-2). As the major country, under non-cooperative management, the U.S. has an incentive to maintain the optimal escapement biomass for future benefits by setting low or even zero catch, while the other two countries benefit from such U.S. conservation efforts. After any delay, once the three countries are engaged in cooperative management, the U.S. engages in rebuilding the biomass up to the optimal escapement biomass, for future benefits. As it turns out then costs to the U.S. to rebuild or maintain the optimal escapement biomass are

incurred regardless of how many years of delay there are in cooperative management. On top of the cost of rebuilding the biomass for all years, there is also economic loss due to an inability to achieve optimal escapement biomass, an added cost for the U.S.

While the cost to the U.S. is significant, the costs to Canada and Mexico appear to be negative except for Canada, for more than a 20th-year of delay in the time-increment SST scenario (Table 4-1). The negative cost implies that Canada and Mexico benefit by delaying cooperative management. For SSTs up to 19.5 °C in the time-increment SST scenario and down to 16.7 °C in the time-decrement SST scenario, Canada and Mexico are always minor countries, i.e., they always have less than half of the biomass distribution within their waters (Figure 4-2). As minor countries, Canada and Mexico benefit from engaging in non-cooperative rather than cooperative behavior. Under non-cooperative management, the conservation efforts by the U.S. to maintain the optimal escapement biomass bring benefits to Canada and Mexico.

In the time-increment scenario with $r = 0.03$ and 0.05 (Figure 4-3 and Table 4-1), the delay of cooperation beyond the 10th and 20th years respectively left Canada with the cost of rebuilding up to the optimal escapement biomass. This is because the stochastic time-increment SST scenario shifted biomass towards Canada and made Canada the major country, hence the cost of

rebuilding a biomass to the optimal escapement biomass appears as costs for Canada (e.g., 3.7 million USD for a 25th-year of delay in Table 4-1). The results of the time-decrement scenario with $r = 0.03$ showed a similar result for Mexico because the stochastic time-decrement SST scenario shifted the biomass distribution into Mexican waters (Figure 4-4).

Sensitivity analysis using different discount rates ($r = 0.03, 0.05, 0.1$ and 0.15) showed identical trends for the time-increment and time-decrement scenarios except for the costs to Canada when $r = 0.03$ and $r = 0.05$ in the time increment SST scenario, and Mexico when $r = 0.03$ in the time decrement SST scenarios (Figures 4-3 and 4-4). Due to the discounting of the future net benefits, one would expect less net benefit and less cost for delaying cooperation for higher discount rates (e.g., $r = 0.15$). This is explicitly confirmed in the modeled total costs and the costs for the U.S. for both time-increment and time-decrement SST scenarios. Both ocean climate scenarios showed the same trends for the total cost, the costs to the U.S and Mexico as well as for the conservation risk (Tables 4-3 and 4-4). At the end of the 35-year simulations, under both the time-increment and time-decrement scenarios SSTs are expected to be 19.5 °C and 16.4 °C, respectively, without stochastic disturbance (see Equation 4-6). In this case, the U.S. emerges as the major country with more than half of the biomass distribution (Figure 4-2).

In both climate scenarios, the cost of delaying cooperation with $r = 0.15$ yielded less negative results than when $r = 0.1$ for Canada and Mexico (Figures 4-3 and 4-4). In addition to the net economic benefits of a higher discount rate, higher discounting drives the optimal escapement biomass level lower. The lower escapement biomass set by the U.S. leads to less spillover benefits for Canada and Mexico, which then results in less negative costs for Canada and Mexico. The conservation risks shown in Tables 4-3 and 4-4 confirmed a lower biomass under $r = 0.15$ relative to other discount rates in both ocean climate scenarios.

4.4 Discussion

The purpose of this study was to compute the cost of delaying cooperative management of Pacific sardine in the CCE under the influence of ocean climate variability.

Two significant costs of delaying cooperative management are, 1) loss of the economic benefit that can be gained by maintaining the optimal biomass for future benefits; and 2) the costs incurred to rebuild stocks to the optimal escapement biomass once they are depleted by an extended period of non-cooperative management. As the years of delaying cooperative management increased, more drastic conservation efforts were required to replenish the fish

stock to the optimal escapement biomass. The U.S. bears the cost of restoration because of its status as the major resource holder under both ocean climate scenarios.

The study clearly suggested that Canada and Mexico have less incentive to engage in cooperative management on the grounds that these countries actually benefit from non-cooperation. On the other hand, this study demonstrated that the U.S. has significant incentive to engage in cooperative management immediately.

As Miller and Munro (2004) noted, the predictions of the impacts on a fish stock and the economic benefits to participants in shared fish stock fisheries are keys for cooperative behavior. Our results demonstrated the potential cost incurred from delaying cooperative management given ocean climate variability. Although it is not the precisely defined cost, our estimated cost of delaying cooperative management and the conservation risk would be information useful toward engaging the three countries in cooperative management. Miller (2007) suggests that a key in cooperative management of a transboundary fish stock is to maintain each country's incentives to cooperate, despite changes in fish availability. The significant costs incurred by the major country for resource share (the U.S.) provides a strong incentive for cooperative management; conversely, the negative costs for minor countries for resource share (Canada and

Mexico) explicitly suggest that there is less incentive for them to cooperate. Our results suggested that a key for achieving cooperative management of a transboundary fish stock under ocean climate variability, establishing the means by which a major country for resource share can motivate minor countries for resource share to engage in cooperative fishing behavior.

4.5 Conclusion

In this study, simulations of a three-country transboundary fishery for Pacific sardine, which incorporate ocean climate variability in the CCE, revealed the potential cost of delaying cooperative management by participants in the fishery.

Our choices for fishery resource management with ocean climate variability are always a combination of reducing fishing pressure and increasing the capacity of fishing participants to cope with the impacts of changes to a fish stock. While a sole resource user of a fish stock is expected to have much more control over the conservation and management response to such circumstances, this situation presents much more of a challenge when conservation and management of the stock involves multiple competing countries with diverse economic incentives. Our study revealed that most of the cost of delaying cooperative management is

incurred by the country that has the dominant share of a transboundary fish stock. Hence, that is the country that should take the initiative to bring about cooperative management.

Looking to the past, in the late 1940s, Pacific sardine landings started to decline dramatically and the sardine stock shifted southward. The subsequent collapse of Pacific sardine fishery has been attributed to a combination of overfishing and the occurrence of a cold regime in the CCE. During the 1970s, all Pacific sardine fisheries were closed in the U.S. As the CCE may be in the initial stages of a new cold regime, this study concludes that vigorous action towards cooperative management is needed now, before the cost of delaying cooperative management of the Pacific sardine resource reflect what was experienced from the 1940s through the 1960s.

It is noted that the far-reaching process of building cooperative fishery management among multiple countries will be extremely challenging due to political considerations and diverse economic motivations. It is suggested that future studies of cooperative exploitation need to further address the costs and the risks that result from ocean climate variability.

Table 4-1 The cost (million USD) of delaying cooperative management to each country separately and collectively in the time-increment SST scenario with discount rates, $r=0.05$. Note that the total payoffs slightly may differ from the sum of the three countries' costs due to rounding.

<i>Cost of i^{th}-year delay of cooperative management in the 35-year projection (million USD)</i>								
	<i>1</i>	<i>5</i>	<i>10</i>	<i>15</i>	<i>20</i>	<i>25</i>	<i>30</i>	<i>35</i>
<i>Total</i>	2.0	18.8	45.5	66.0	81.2	88.1	84.8	81.8
<i>CAN</i>	-5.1	-22.9	-17.6	-9.6	-0.8	3.7	2.8	2.7
<i>US</i>	17.1	69.3	94.6	104.5	109.2	110.5	108.2	106.0
<i>MX</i>	-10.0	-27.6	-31.4	-29.0	-27.3	-26.2	-26.2	-26.9

Table 4-2 The cost (million USD) of delaying cooperative management for total and each country in the time-decrement SST scenario with discount rates, $r=0.05$. Note that the average total payoffs slightly may differ from the sum of the three countries' costs due to rounding.

<i>Cost of i^{th}-year delay of cooperative management in the 35-year projection (million USD)</i>								
	<i>1</i>	<i>5</i>	<i>10</i>	<i>15</i>	<i>20</i>	<i>25</i>	<i>30</i>	<i>35</i>
<i>Total</i>	2.1	18.0	42.1	60.9	74.3	80.6	78.5	74.5
<i>CAN</i>	-5.3	-25.2	-28.4	-26.4	-24.8	-21.7	-22.9	-23.6
<i>US</i>	17.3	67.8	91.4	101.6	106.4	107.1	85.9	103.3
<i>MX</i>	-10.0	-24.6	-20.9	-14.3	-7.3	-4.7	-3.9	-5.2

Table 4-3 The conservation risk (%) for the time-increment SST scenario - probability that the biomass falls below 10 % of the initial biomass (1.2 million tonnes) at least once over the 35-year simulation.

Discount rate	<i>Conservation index of delaying t^{th} -year in cooperative management (%)</i>							
	<i>1</i>	<i>5</i>	<i>10</i>	<i>15</i>	<i>20</i>	<i>25</i>	<i>30</i>	<i>35</i>
<i>0.03</i>	0.0	1.6	5.1	13.8	23.7	32.3	39.2	44.0
<i>0.05</i>	0.0	1.6	5.3	13.4	24.3	33.0	38.7	43.8
<i>0.1</i>	0.0	2.2	8.1	18.2	27.9	36.8	43.0	48.3
<i>0.15</i>	0.0	4.3	16.3	30.7	41.3	48.5	53.9	58.3

Table 4-4 The conservation risk (%) for the time-decrement SST scenario - probability that the biomass falls below 10 % of the initial biomass (1.2 million tonnes) at least once over the 35-year simulation.

Discount rate	<i>Conservation index of delaying t^{th} -year in cooperative management (%)</i>							
	<i>1</i>	<i>5</i>	<i>10</i>	<i>15</i>	<i>20</i>	<i>25</i>	<i>30</i>	<i>35</i>
<i>0.03</i>	0.0	1.4	5.2	13.9	22.5	31.1	37.5	41.6
<i>0.05</i>	0.0	1.6	5.6	14.2	23.4	31.6	38.2	42.4
<i>0.1</i>	0.0	2.2	8.0	18.7	27.9	36.6	41.7	46.6
<i>0.15</i>	0.0	4.2	16.4	31.0	41.4	47.4	54.6	56.7

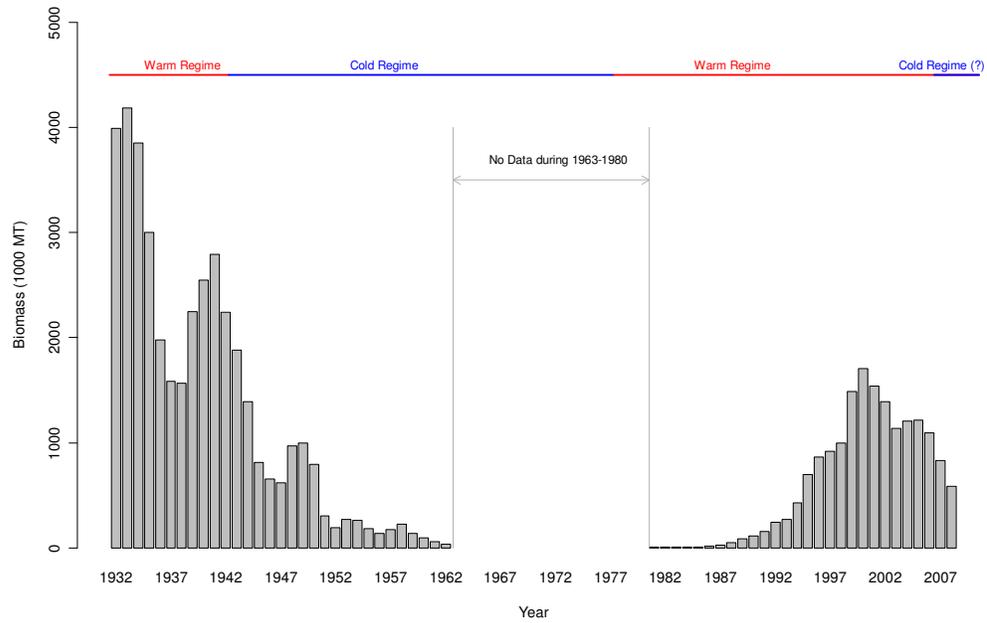


Figure 4-1 Biomass changes of Pacific sardine over time (biomass data from Hill *et al.*, 2009) and the climate regime in the California current ecosystem.

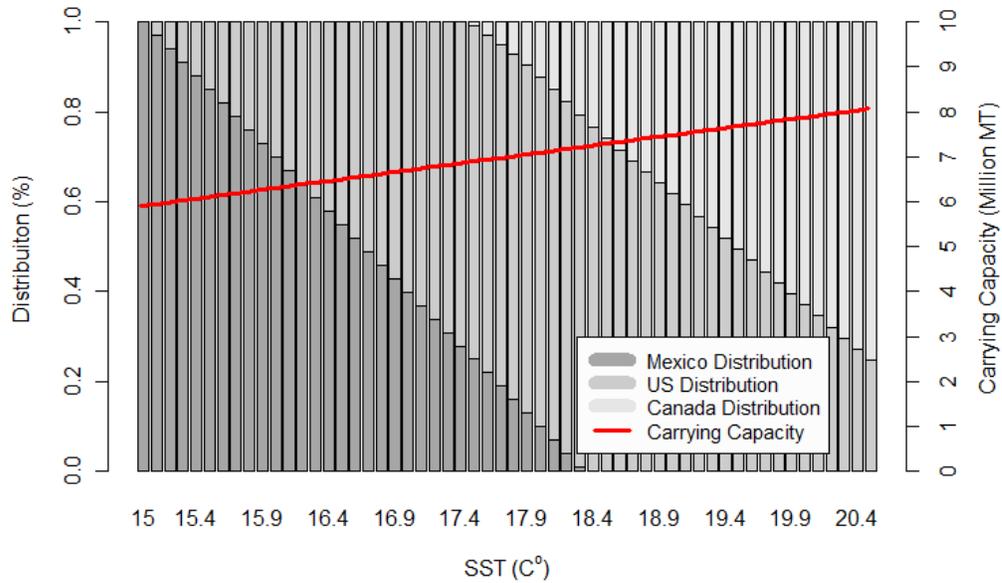


Figure 4-2 Development of the modeled biomass distribution and carrying capacity in accordance with the SST.

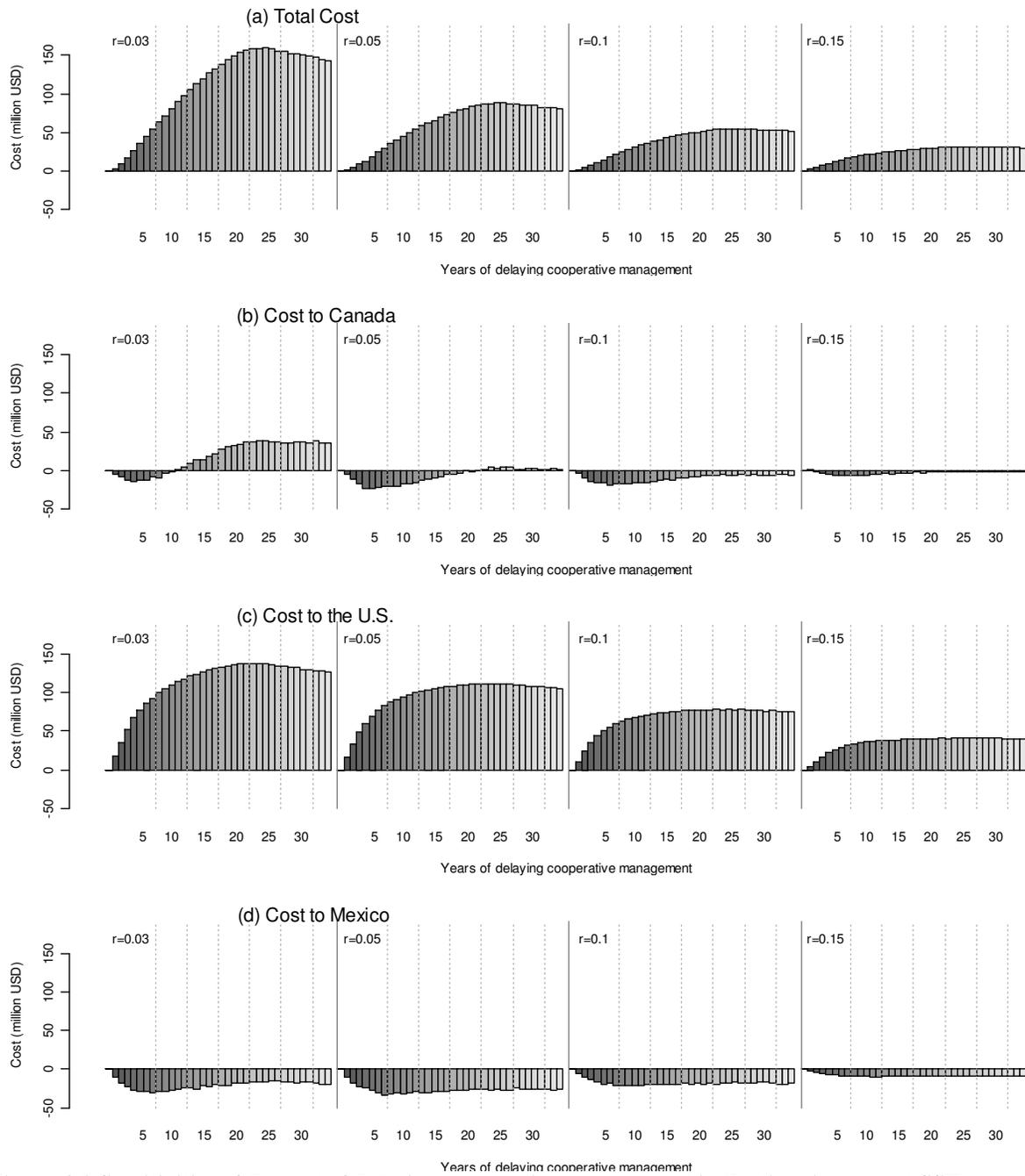


Figure 4-3 Sensitivities of the cost of delaying cooperative management in the time-increment SST scenario with four discount rates ($r=0.03, 0.05, 0.1$ and 0.15).

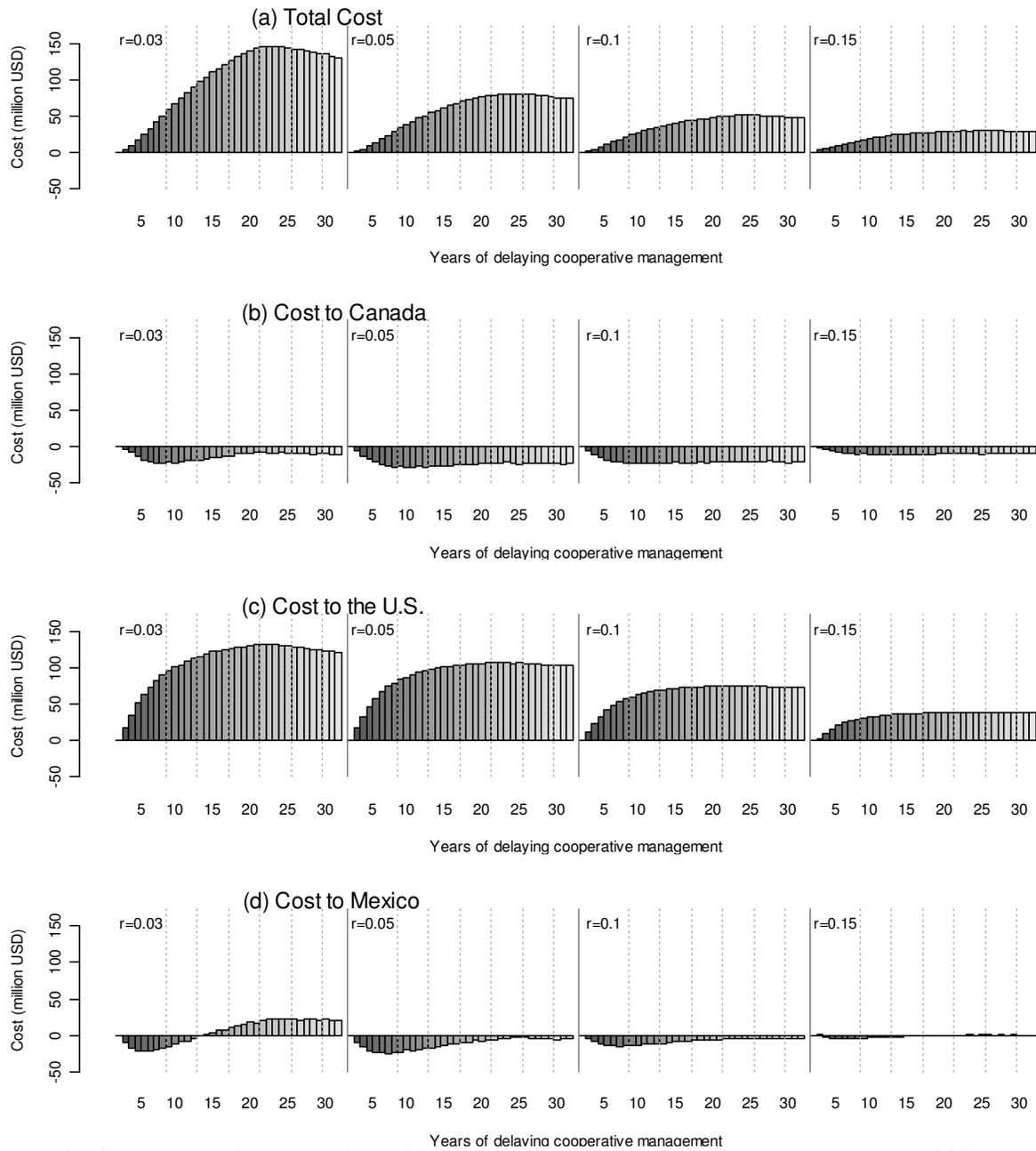


Figure 4-4 Sensitivities of the cost of delaying cooperative management in the time-decrement SST scenario with four discount rates ($r=0.03$, 0.05 , 0.1 and 0.15).

Chapter 4 references

Brander, K.M. 2007. Global fish production and climate change. *Proceeding of National Academy of Science* 104(50): 19709-19714.

Brander, K. 2009. Impacts of climate change on fisheries. *Journal of Marine System* *in press* 2008.12.015

DFO (Fisheries and Oceans Canada). 2004. Stock status report 2004/037. Report 037.

Field, J., and R. Francis. 2002. Cooperating with the environment: Case studies of climate and fisheries in the northern California current. *American Fisheries Society*, Bethesda MD.

Fox, W. W. 1970. An exponential yield model for optimizing exploited fish populations. *Transactions of the American Fisheries Society* 99:80-88.

Felix-Uraga, R., V. M. Gomez-Munoz, C. Quinonez-Velazquez, F. N. Melo-Barrera, and W. Garcia-Franco. 2005a. On the existence of Pacific sardine groups off the west coast of Baja California and southern California. *Reports of California Cooperative Oceanic Fisheries Investigations* 45:146-151.

Felix-Uraga, R., C. Quinonez-Velazquez, K. T. Hill, V. M. Gomez-Munoz, F. N. Melo-Barrera, and W. Garcia-Franco. 2005b. Pacific sardine (*Sardinops sagax*) stock discrimination off the west coast of Baja California and southern California using otolith morphometry. *Reports of California Cooperative Oceanic Fisheries Investigations* 46:113-121.

Hannesson, R. 2005. Global warming and fish migrations. Institute for Research in Economics and Business Administration, N01/05

Hannesson, R. 2006. Individual rationality and the “zonal attachment principal”: Three stock migrate models. *Resource and Environment Economics* 34: 229–245.

Hill, K. T., N. C. H. Lo, B. J. Macewicz and R. Felix-Uraga. 2007. Assessment of the Pacific sardine (*Sardinops sagax caerulea*) population for U.S. management in 2006. *NOAA Technical Memo. NOAA-TM-NMFS-SWFSC-386*. 75p.

Hill, K. T., N. C. H. Lo, B. J. Macewicz and R. Felix-Uraga. 2008. Assessment of the Pacific sardine (*Sardinops sagax caerulea*) population for U.S. management in 2007. *NOAA Technical Memo. NOAA-TM-NMFS-SWFSC-413* 185p

Hill, K. T., N. C. H. Lo, B. J. Macewicz and R. Felix-Uraga. 2009. Assessment of the Pacific sardine resources in 2008 for U.S. management in 2008. forthcoming as NOAA Technical Memo.

Herrick, S., Norton, J., Mason, J.E., and C. Bessey. 2007. Management application of an empirical model of sardine-climate regime shifts. *Marine Policy* 31(1): 71-80.

Ishimura, G., U.R. Sumaila, and S. Herrick. 2010. Fishing games under climate variability: Transboundary Management of Pacific sardine in the California Current Ecosystem. *Fisheries Center Working Paper # 2010-1*, The University of British Columbia, Vancouver, B.C., Canada.

Jacobson, L.D., and A.D. MacCall. 1995. Stock-recruitment models for pacific sardine (*sardinops sagax*). *Canadian Journal of Fisheries and Aquatic Sciences* 52(3): 566-577.

Jacobson, L.D., S.J. Bograd, R.H. Parrish, R. Mendelsohn, and F.B. Schwing, 2005. An ecosystem-based hypothesis for climatic effects on surplus production in California sardine (*Sardinops sagax*) and environmentally dependent surplus production models. *Canadian Journal of Fisheries and Aquatic Sciences* 62(8): 1782-1796.

Laukkanen, M. 2003. Cooperative and non-cooperative harvesting in a stochastic sequential fishery. *Journal of Environmental Economics and Management* 45(2): 454-473.

McFarlane, G. A., J. R. King, and R. J. Beamish. 2000. Have there been recent changes in climate? Ask the fish. *Progress in Oceanography* 47(2-4):147-169

Miller, K.A. 2007. Climate variability and tropical tuna: Management challenges for highly migratory fish stocks. *Marine Policy* 31(1): 56-70.

Miller, K.A., and G.R. Munro. 2004. Climate and cooperation: A new perspective on the management of shared fish stocks. *Marine Resource Economics* 19(3): 367-393.

Munro, G.R., A. Houtte, R. Willmann. 2004. The conservation and management of shared fish stocks: Legal and economic aspects. *FAO Fisheries Technical Paper*, Rome Italy.

Norton, J. G. and J. E. Mason. 2005. Relationship of California sardine (*Sardinops sagax*) abundance to climate-scale ecological changes in the California Current Ecosystem. *California Cooperative Oceanic Fisheries Investigative Report* 46: 83-92.

Pacific Fishery Management Council. 1998. Amendment 8 (to the northern anchovy fishery management plan) incorporating a name change to: *The Coastal Pelagic Species Fishery Management Plan*. Pacific Fishery Management Council, Portland, OR.

Quinn, T. J., and R. B. Deriso. 1999. Quantitative fish dynamics. Oxford University Press, New York.

Sumaila, U.R. 1997. Cooperative and non-cooperative exploitation of the Arcto-Norwegian cod stock in the Barents Sea. *Environmental and Resource Economics*, 10, 147-165.

Wolf, P. 1992. Recovery of the Pacific sardine and the California sardine fishery. *Reports of California Cooperative Oceanic Fisheries Investigations* 33:76-86.

World Bank. 2009. The Cost to Developing Countries of Adapting to Climate Change: New Methods and Estimates, the Global Report of Economics of Adaptation to Climate Change Study, World Bank, Paris, France.

CHAPTER 5. CONCLUSION

5.1 Discussion

Challenges to the management of transboundary fishery resources, which are shared by more than one country, are compounded by biological uncertainties associated with marine environmental and ocean climatic variability, as well as by the diversified economic interests among and within participating countries (Munro *et al.*, 2004). Further, ocean climate variability produces distinctive and different effects on transboundary fishery resources within and between countries.

As a result of ocean climate regime shifts in the CCE, the survival of Pacific sardine and consequently the viability of the fishing industries and the communities in Canada, the U.S. and Mexico that depend on this transboundary fish stock are threatened. A necessary condition to ensure the survival of Pacific sardine stocks and maximize the economic benefits from the industry brings is to establish fully cooperative fisheries management by the three countries. The three essays on Pacific sardine in this dissertation collectively analyze the opportunities and challenges – economic and biological – that face the three nations. This dissertation is intended to inform the appropriate authorities in the countries about the need to establish a high degree of cooperative management in order to reduce the chances of future collapses of Pacific sardine and the loss of achievable economic benefits.

In chapter 2, the results suggest that the incentives to establish a dynamic transferable individual catch share system depends on domestic resource utilization priorities and the fisheries policies of each country. Although transboundary conservation and management under a dynamic individual catch share system under cooperative management is likely to maximize total benefits, contradictory results in terms of economic outcome for each country, were obtained from either fixed shares or dynamic shares of an annual individual catch. Other issues with an individual catch share system have to do with the transaction costs of establishing a market for individual catch shares or in devising a system for side payments. The results also indicate that there are challenges to establishing initial individual catch shares for a shared fish stock among the participating countries when the effects of climate variability on the size of the stock and its boundaries are factored in.

Chapter 3 revealed that stand-alone stability of a grand coalition to exploit Pacific sardine cannot be achieved under a regime of ocean climate variability. However, our results suggest that side payments can be an incentive for cooperation, and that side payments led by a stable stand-alone coalition of a two country coalition or by the largest beneficiary of a fishery can provide the incentive to form a grand coalition.

Chapter 4 demonstrated the potential costs incurred by delaying cooperative management given ocean climate variability. Our estimated economic cost of delaying cooperative management, coupled with the conservation risk, increased the longer cooperative management was delayed. Further, significant costs were incurred by the dominant resource holder, the U.S., which suggests a strong incentive for cooperative management by the U.S.. Conversely, the lesser costs for the minor resource holders (Canada and Mexico) explicitly suggest there is less incentive for them to cooperate. Similar to our conclusions regarding side payments (Chapter 3), the results suggest how a major resource holder can motivate minor resource holders by giving them incentives to engage in cooperative behavior.

Consistently, throughout the three essays, it was shown that a high degree of cooperative management outperforms all other options in achieving the desired results. The outcomes from non-cooperative management of Pacific sardine were inferior from both an economic and resource conservation perspectives. Moreover, our major/minor player model, which explicitly assumes heterogenous management interests, suggested that unilateral efforts by the dominating resource shareholder toward conservation would not be successful given the competitive motivations of the minor resource shareholders. Since these studies show considerable free-rider

benefits being garnered by Mexico and Canada, both countries have substantial motivation to avoid cooperative management.

It should be noted that the magnitude of the time-variant fish share, even engaging in non-cooperative management, the legal frameworks of the U.S. and Canada¹⁵ (i.e., Magnusson-Stevens Fishery Conservation; NOAA 2007 and Management Act for the U.S. and Species at Risk Act for Canada; Ministry of Justice 2009) would prevent fishers in the U.S. and Canada from overfishing of Pacific sardine resources.

One impediment, however, that would impact the ability of these two countries to effectively prevent over-exploitation as a result of ocean climate variability is the framework under which the laws are implemented. Both U.S. and Canadian conservation regulations to prevent overfishing require multiple procedures to either set catch limits to prevent overfishing or to recognize Pacific sardine as an endangered species. These regulations include extensive scientific review by experts. Consequently, the time required by Canada and the U.S. to officially acknowledge the existence of changes in ocean climate variability, compounded by the additional time required to implement fishing restrictions would severely inhibit the effectiveness of the conservation effort of Pacific sardine. Moreover, as this study suggests,

¹⁵ So far, we are not aware of relevant legal frameworks for the conservation of Pacific sardine in Mexico. It, however, would have relevant legal frameworks to protect fisheries resources in general, which can be applied for Pacific sardine.

unilateral conservation and management would not be achievable due to depletions by free-riders. Therefore, conservation efforts driven by a sole participant as stimulated by domestic policy cannot succeed without cooperative management efforts by the all three countries.

A first step in the adaptation of cooperative management by the three countries would be an agreement on the current status, distributions and abundance of Pacific sardine and the anticipated future changes as Miller and Munro (2004) suggested. For example, the coastal Pacific hake, which is another transboundary fish shared by the U.S. and Canada, was overexploited during the 1990s by the U.S. and Canada because of disagreements over the share of acceptable biological catch (Helsler *et al.*, 2008). A joint US-Canada treaty for the Pacific hake was formally ratified in 2003. Fixed allocations of the total allowable catch were set at 26% for Canada and 74% for the U.S. While fixed allocation could be set and agreed to for Pacific hake, managing the Pacific sardine to maximize potential economic rent while avoiding overexploitation requires setting dynamic allocations that correspond to changes if the distribution of Pacific sardine induced by ocean climate variability. However, as our current ability to predict future changes in ocean climate variability and our knowledge of the biological functions of Pacific sardine are limited, the likelihood of establishing effective cooperative management of Pacific sardine is extremely challenging.

Overall, the two key messages of the three chapters are, 1) although cooperative management would maximize both economic and conservation benefits under a regime of ocean climate variability, it would be difficult to be achieved; and 2) the dominant beneficiary(s) needs to be motivated to initiate side payments to protect its own economic benefits. Miller (2007) concluded that it is necessary to maintain incentives of a country to cooperate despite changes in fish availability. Our study extends this result by identifying which participants should take the initiative toward cooperative management of a transboundary fish stock under ocean climate variability.

5.2 Future work

The ability to make predictions on the estimated effects of ocean climate variability on Pacific sardine, and a methodology to determine precise catch or economic outcome are not the goal of this study. Rather, the aims of the three chapters are: to illustrate the conservation and economic benefits possible from full and partial cooperative management of Pacific sardine by Canada, the U.S. and Mexico; and to provide useful information toward establishing full cooperative management of Pacific sardine under a regime of ocean climate variability.

A major feature of this study is its utilization of game theory to look at various transboundary conservation and management schemes for Pacific sardine under a regime of ocean climate variability. Because of 1) the limited data available to quantify precise relationships between the distribution and abundance of Pacific sardine and ocean climate variability in the CCE; and 2) the uncertainties of ocean climate variability, it is reasonable to expect that our findings do not provide reference points or objectives for the management of Pacific sardine. The collection and availability of additional data to quantify the precise relationship between the abundance and distribution of the Pacific sardine and ocean climate variability in the CCE would make the results from the three studies more appropriate as reference points.

Additionally, the model this study presents does not account for two economic components. First, the cost of fishery operations for each country relative to local abundance was not included. This study assumed identical costs for the three countries, independent of local abundance. Secondly, this study does not account for the fishing capacity of each country. Although the catch of Pacific sardine goes mainly to global markets, there may be limits to demand, as well as the willingness to make investments in the expansion of fishing capacity. Further analyses in these directions would improve the relevance of the results obtained.

Finally, this study included only changes to the SST as they affect the carrying capacity and distribution of the Pacific sardine stock. In practical fishery management and operations, managers and fishing operators must make decisions in the face of a larger set of uncertainties (NRC 1998). To evaluate the consequences of different actions, managers need to consider both biological and economic uncertainties. In addition, the uncertainty as to when shifts in ocean climate variability occur, as well as other factors, must be accounted for. However, by replacing probability distributions based on various uncertainties (Clark 2003), this study can be extended using Bayesian decision analysis, a useful tool for decision makers facing uncertainties.

In the next few decades, we anticipate additional impacts from ocean climate variability, not only on the Pacific sardine, but on other fishery resources in the CCE that would be similarly vulnerable. As Miller and Munro (2004) emphasized, anticipation of changes in fishery resources under ocean climate variability is key to international fisheries management. This study can be further developed with updated economic and biological data and relevant studies of the Pacific sardine with the goal of providing more useful information to those in Canada, the U.S. and Mexico responsible for implementing robust management of Pacific sardine under ocean climate variability.

Chapter 5 references

Clark, W.C. 2003. *The Worldwide Crisis in Fisheries: Economic Models and Human Behavior*, Cambridge, Cambridge University Press.

Hlser, T.E., I.J. Stewart, and O.S. Hamel. 2008. Stock assessment of Pacific hake (a.k.a Whiting) in U.S. and Canadian Waters in 2008.

http://www.pcouncil.org/groundfish/gfsafe1008/pacific_hake_assessment_2008_FINAL.pdf as of January 10 2010.

Miller, K.A. 2007. Climate variability and tropical tuna: Management challenges for highly migratory fish stocks. *Marine Policy* 31(1): 56-70.

Miller, K.A., and G.R. Munro. 2004. Climate and cooperation: A new perspective on the management of shared fish stocks. *Marine Resource Economics* 19(3): 367-393.

Ministry of Justice (CANADA). 2009. Species at Risk Act.

<http://laws.justice.gc.ca/PDF/Statute/S/S-15.3.pdf> as of January 10 2010.

Munro, G.R., A. Houtte, and R. Willmann. 2004. The conservation and management of shared fish stocks: Legal and economic aspects. *FAO Fisheries Technical Paper*, Rome Italy.

National Oceanic and Atmospheric Administration, U.S. Department of Commerce. 2007. Magnuson-Stevens Fishery Conservation and Management Act as amended through January 12, 2007:

http://www.nmfs.noaa.gov/msa2005/docs/MSA_amended_msa%20_20070112_FINAL.pdf as of January 10 2010.

National Research Council (U.S.). Committee on Fish Stock Assessment Methods. 1998 .

Improving fish stock assessments, National Research Council. 98. Washington, D.C., National Academy Press.

APPENDIX A: BASIC ECOLOGY OF PACIFIC SARDINE

A.1 Introduction

Sardines (*Sardinella*, family Clupeidae), also known as pilchards, are small pelagic schooling fishes, with 18 main species recognized worldwide (DFO 2004). They are a warm-water species, and their distribution extends widely between the latitudes of 60°N and 50°S around the shores of every continent (Culley 1971). One dominant sardine species in the highly productive large scale marine ecosystems of the Alguhas, Benguela, California, Kuroshio and Peru currents is *Sardinops sagax* (Parrish *et al.*, 1989).

Landings of sardines worldwide exhibited significant decadal fluctuations due to extreme variability of stock abundance. This variability appears to be composed of 20-30 year cycles of reiterating boom and bust (Chavez *et al.*, 2003). Researchers have argued that the trigger for this cycle is climate regime shifts with populations sardine flourishing in warm climate regimes and depressed in cold climate regimes. Moreover, several studies have suggested that low sardine abundance has been followed by dramatic increases in anchovy stocks (e.g., Bakun and Weeks 2004; Chavez *et al.*, 2003; Herrick *et al.*, 2007; Norton and Mason 2005).

Pacific sardine (*Sardinops sagax*), or the California pilchard, has been one of the most abundant fish in the California Current Ecosystem (the CCE) since the late 1990s. The history of its

abundance is similar to other sardine stocks in the world. During the 1930s and 1940s, in the warm regime of the CCE, landings of Pacific sardine supported the largest fishery in the Eastern Pacific Ocean and peaked with over 700,000 tonnes landed in the 1936 and 1937 fishing seasons. During 1934 and 1944, the estimated biomass of the Pacific sardine varied between 1.2 million and 2.8 million tonnes (Hill *et al.*, 2006). In the late 1940s, landings started to decline dramatically, and the sardine fishery collapsed. Originally, overfishing was blamed for the collapse of Pacific sardine. Now it is believed that, along with intensive fishing pressure, the beginning of a cold regime shift in the CCE during the 1940s decreased the biological productivity of Pacific sardine and accelerated the collapse of the stock. The collapse of Pacific sardine, therefore, is attributed to a combination of overfishing and low biological productivity due to a cold regime (Herrick *et al.*, 2007). In 1974, a moratorium was announced in the U.S., closing the Pacific sardine fishery (Wolf 1992). The abundance of Pacific sardine remained below 5,000 tonnes during the 1950s and 1960s. When a warm regime of the CCE appeared in the late 1970s, the Pacific sardine stock began to rebuild, resulting in the moratorium being lifted in 1986. It is estimated that the biomass peaked at 1.56 million tonnes in 1996-7. The total catch has remained greater than 120,000 tonnes since 2000.

Along with spectacular changes in abundance, the geographical distribution of Pacific sardine has also exhibited tremendous variability. From the mid-1940s through the mid-1990s, when stock abundance was low, the distribution of the sardine was restricted to Baja California, Mexico to Monterey, California, US. In the mid-1990s, as the population began to recover, the distribution expanded northward, as far as Vancouver Island, Canada (Hill *et al.*, 2006; Ware 2004; DFO 2004). Pacific sardine is currently distributed from Baja California, Mexico to South of Alaska over three jurisdictions; Mexico, U.S. and Canada. This implies that as the Pacific sardine stock increased, the spatial distribution expanded further north. In contrast, as the Pacific sardine stock collapsed, its spatial distribution was limited to southern and Baja California. The future of Pacific sardine distribution is unknown, and changes in abundance and distribution affect the availability of the Pacific sardine for local fisheries in three jurisdictions.

Two unique biological uncertainties, dramatic variations in abundance and geographical distribution, for Pacific sardine, impose challenges in the current management of this fishery. The primary purpose of this paper is to investigate these two uncertainties and the challenges they pose to Pacific sardine management. In doing so, this appendix reviews literature relating to the biological characteristics of Pacific sardine and identifies management challenges.

A.2 Biology of Pacific sardine

Pacific sardine has a silvery body with black spots visible through the scales (Figure A-1). Sardines are omnivorous filter feeders. They prey on phytoplankton (e.g., diatoms), zooplankton (e.g., copepods) and occasionally fish larvae (DFO 2004). They actively form tight schools (Culley 1971) and avoid fishing nets so fisheries are mostly conducted at night when the lighting is limited (Schweigert 2002). Pacific sardine may live as long as 14 years, but the majority of individual fish do not exceed 30 cm in length (Hill *et al.*, 2006).

This first section defines the study's target stock within recognized Pacific sardine stocks and reviews the life history of the northern stock of Pacific sardine and the migration pattern associate with its life history.

A.2.1 Stock structure and the target stock

At present, the stock structure of Pacific sardine found in the CCE is still under discussion. It is widely recognized and accepted that at least three substocks of Pacific sardine inhabit in the CCE (Felix-Uraga *et al.*, 2005a; 2005b). These are the 1) northern substock, distributed from northern Baja California to South eastern Alaska, 2) southern substock, distributed from Baja California to southern California and 3) Gulf of California substock, distributed within the Gulf

of California. Vrooman (1964) did serological studies and concluded these three stocks are significantly different because of a variation of the C-positive blood factor. Hedgecook *et al.* (1989) did a genetic and morphometric study for these stocks. Despite morphometric differences (e.g., geographic cline in size-at-age), their electrophoresis techniques found that there is no genetic variation among these stocks. They concluded that morphometric heterogeneities of the three substocks may be determined environmentally (e.g., life history) and not genetically.

The annual migrations of all three stocks, from south to north, occur almost simultaneously. This prevents the three substocks from overlapping in habitat and better enables us to distinguish between them (Hill *et al.*, 2006). The U.S. Coastal Pelagic Species Fishery Management Plan (CPS-FMP) includes only the northern stock which is mainly exploited by the Canadian, U.S. Northwest (Washington and Oregon), the California and northern Baja California fisheries (PFMC 2007). As such, the focus of this paper is the northern substock of Pacific sardine.

A.2.2 Life history of northern stock of Pacific sardine

Knowledge of an exploited fish species' life history is indispensable information for fisheries managers. Solid information about the early life stages, for instance locations of spawning grounds or the reproductive ability of individual mature fish, influences the decisions of fisheries managers. Although research efforts have been devoted to Pacific sardine since 1930's, solid information remains elusive due to the dramatic changes in abundance and distribution.

A single female Pacific sardine hatches around 200,000 eggs per spawn which occur in three batches per year in the mid-water layer. Eggs drift two to four days before hatching, a process that requires a relatively warm range of water temperature, generally between 14 C° and 16 C° (DFO 2004). The most intensive spawning of the northern stock occurs from January to September, but is mainly concentrated in April and May period off the coast of Southern California. The spawning occurs between Point Conception and Ensenada, a stretch about 400 km long and extending up to 325 km offshore (Culley 1971; Ware 2004). Hill *et al.* (2006) pointed out that seawater temperature influences the spatial and seasonal distribution of spawning activities. During the warmer water regime in the CCE, the center of the spawning ground shifts northward, and the spawning period is extended. Occasional spawning activities in Canadian waters, Oregon and Washington (around the Columbia River) have occurred when

abundance is high during warm years (El Niño). This fact would support the concept that seawater temperature affects spawning activities (Emmett *et al.*, 2005, McFarlane *et al.*, 2005). These northern spawning grounds, however, are not recognized as normal.

Pacific sardine larvae are about 3.5 mm initially and grow to around 34 mm after two to three months. By the end of first year, the length of larvae reaches 115 mm (Culley 1971). The larvae have limited mobility due to currents, and inhabit the area along the southern California coast, where the primarily spawning grounds are located. The young fish spend their first two years of life off the Southern California coast (Ware 2004). This has not been reconfirmed in recent years and may have changed. After two years, they begin their annual migration north during summer, and back south in the autumn. However, Hill *et al.* (2006) stated that the age of maturity of Pacific sardine declines with a decrease in biomass. At a relatively low abundance, the maturity age is one year, while maturity is reached at age two when stocks are highly abundant (cited from Butler 1987 and MacCall 1979). Lo *et al.* (2005) reported that from 1994 to 2004, the age at 50 % maturity increased from age 1 to 2, when Pacific sardine exhibited a significant increase in abundance.

A.2.3 Migratory behaviour

It is well recognized that Pacific sardines have different migratory behaviour depending on their age and size. Each successive year, under a warm regime in the CCE, older and larger sardines migrate further northward toward rich feeding grounds before travelling south again (Hill *et al.*, 2006). Although identifying the migration behaviour of Pacific sardine is crucial for international management of Pacific sardine, there has only been one coast-wide tagging study which occurred in the late 1930's and is available from the Bureau of Marine Fisheries (1945). This study was done during a warm regime, a time when Pacific sardine flourished. While they could not get a large enough number of recaptures to quantify a detailed migration pattern and rate, the study observed;

- 1) Fish tagged in Mexican waters were caught in the California fishery off San Diego, San Pedro, Monterey and San Francisco;

- 2) Fish tagged in central and Southern California were caught in all California fisheries as well as in the Pacific northwest which included Oregon, Washington and British Columbia;

- 3) Fish tagged in British Columbia and Oregon were caught in the California fisheries;

- 4) The largest sardines migrated from southern California to British Columbia in five to six months and,

- 5) Smaller fish stayed in Southern California before they reached average size.

In recent years under a warm regime, large Pacific sardine reached Canadian waters in mid-June and returned to the spawning ground in Southern California during October (Ware 2004; McFarlane *et al.*, 2005). Instead of annual migrations, during the 1930's, Hart (1937) reported that a small part of the Pacific sardine stock frequently remained in the inlets of Vancouver Island throughout the winter. With the recent re-expansion years, some Pacific sardine remain year –around in Canadian and Pacific Northwest waters, and evidence of successful spawning and a juvenile population were observed (Emmett *et al.*, 2005; McFarlane *et al.*, 2005)¹⁶. Due to this age/size-dependent migratory behaviour, the Californian commercial catch is usually dominated by fish less than five years old, while the historical British Columbia commercial catch is dominated by fish six to eight years in age (Hill *et al.*, 2006). Subsequently, the average

¹⁶ Emmett *et al.*, (2005) referred that Pacific sardine spawning in north would be separate stocks from northern substocks.

ages of the catches in Southern California and British Columbia are 3 years and 5.5 years, respectively (Ware 2004).

Chasing more favourable physiological conditions (e.g., temperature, salinity) and food availability may trigger this migration pattern (Schweigert 2002). The causes of this northward migration by older fish are not yet well understood. The timing of the southward migration in autumn may be due to changes in the prevailing winds from an upwelling direction to a downwelling direction (Ware 2004). During a cold regime in the CCE and times of low abundance, the migration of the Pacific sardine is restricted within Southern California and Baja California, and the Pacific sardine is only available for southern California and Mexico.

A.3 Variability in abundance and geographical distribution

Although the detailed mechanism through which temperature affects Pacific sardine stocks is still not fully known, researchers and managers agree that Pacific sardine exhibits variability in abundance and expansion in geographic distribution in accordance with the decadal cold/warm regime shifts in the CCE (Rodriguez-Sanchez *et al.*, 2002; Emmett *et al.*, 2005). The idea that the warm regime increases abundance of Pacific sardine, while the cold regime decreases it, is widely accepted by fishery managers and researchers. However, the detailed mechanism of the

warm/cold regimes shift effect is still under discussions. We expect that the cold/warm regimes of the CCE will continue to shape the variability of abundance and distribution of the Pacific sardine into the future.

A.3.1 Warm-cold regime shifts in the California Current Ecosystem

The CCE extends up to southern Vancouver Island from Baja California and exhibits high biological productivity (Miller and Schneider 2000). The climate of the CCE, over the last century, has been primarily influenced by inter-annual and decadal scale variability, known as the El Niño/Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO), respectively (Field and Francis 2002). Through the last century, the CCE has experienced a shift back and forth from a warm to a cold climate regime in terms of sea surface temperature (McFarlane *et al.*, 2000; Field and Francis 2002; Field 2005). Four regime shifts in the California current are currently proposed and under discussions, 1925, 1947, 1977 and 1988/89. The regime shifts in 1925, 1947 and 1977 were confirmed as major climate regime shifts by several papers (e.g., Hare and Mantua 2000; Mantua 2004), but the climate change in 1988/89 was relatively small and is considered to be a minor regime shift (Minobe 2000). These regimes shifts can be describes as a warm regime from 1925 to the 1947 regime shift, a cold regime

between the 1940s and late 1970s, and a warm regime since 1977 to the present (see example, Figure A-2) (McFarlane and Beamish 2001).

A.3.2 Historical abundance and climate regime

Over the past century, the Pacific sardine stock has exhibited a dramatic boom and bust cycle in abundance. Until the middle of the 1940s, with an annual catch of 500,000 ton, the Pacific sardine resource fueled the largest fisheries in North America. The spawning biomass of Pacific sardine from 1932 through 1934 was estimated as 3.5 million tonnes and varied between 1.2 million to 2.8 million tonnes until the late 1940s. Sudden depletion of the Pacific sardine stock began in 1945. Between the late 1940s and the 1970s, a cold regime shift in the CCE, combined with overfishing by an overcapitalized fishery, led to the collapse of Pacific sardine resources. As a result, a moratorium on the Pacific sardine fishery was called in 1973 (Hill *et al.*, 2006). During the 1950s and 1960s, the coast-wide abundance of Pacific sardine remained under 5,000 tonnes. In the late 1980s, the warm regime shift in the California current system, combined with conservation efforts, resulted in the recovery of the Pacific sardine (Herrick *et al.*, 2007). The spawning biomass started recovering rapidly, and reached around a half million tonnes in 1992. In the past decade (1997-2006), the spawning stock biomass has remained at between 900,000

and 1,300,000 tonnes (Figure A-3). Once again, the Pacific sardine resource is one of the most abundant fishery resources in the CCE.

A.3.3 Abundance and geographical distribution

The annual coast-wide distribution of Pacific sardine is the result of its annual migration behavior as detailed in a previous section. Sardines disappeared from Canadian waters in the late 1940s, as the entire stock collapsed and only re-appeared in 1992, as the range of the resurgent northern stock again expanded to Oregon, Washington and British Columbia. During cold regimes, the stock in the CCE was limited to southern California and Baja California. In 1992, the spawning stock estimate was around 500,000 tonnes (Hill *et al.*, 2006). The Pacific sardine has continued to return to Canadian waters since then.

There are good reasons to think that the increased stock abundance led to the geographical expansion in distribution, rather than assuming an independent relationship between increased abundance and the expansion of geographical distribution (or northward migration). Increased abundance may reduce food availability in the conventional habitats, leading to larger and older fish, which have higher mobility, to find a more favorable environment and migrate further north (Ware 2004). Rodríguez-Sánchez *et al.* (2002) studied the relationship between the

regime shifts between 1931 and 1971 and the Catch per Unit Effort (CPUE) distribution of Pacific sardine in areas off California and Baja-California (see Figure A-4 for coveting areas). Their analysis suggested non-geostationary¹⁷ changes in the abundance distribution along with regime shifts. During the warm regimes (until the late 1940's and from the late 1970's) when the abundance is high, the center of distribution shifted north (see corresponding CPUE distribution in Figure A-5). While during the cold regime (between the late 1940's and the late 1970's) when the abundance is low, the center of distribution shifted south. This study, however, did not cover Oregon, Washington and British Columbia and strictly corresponded to CPUE distribution as a proxy for abundance estimations.

The current U.S. stock assessment assumes a static distribution of the northern stock, with 87 % of the northern stock of Pacific sardine staying in U.S. waters (California, Oregon and Washington) and 13 % staying in Mexican waters (Hill *et al.*, 2006). This 87 % of distribution occurring in the U.S. is based on the average occurrence of egg distribution between the U.S. and Mexico (Hill *et al.*, 1999). In their stock assessment, Hill *et al.* (1999) acknowledged that the limitation of this static geographic distribution is that it is static and does not include Canadian distribution. On the other hand, the Canadian estimation of static distribution is based

¹⁷ Geostationary changes of a fish distribution are described in MacCall (1990) and it forms a symmetric bell curve of the expansion of a fish distribution as biomass increased. Non-geostationary changes suggest a non-symmetric and biased bell peak curve in the expansion of a fish distribution.

on analysis of historical catch and trawl surveys. From 1916 to 1947, 10 % of the total catch of Pacific sardine was taken by Canadian fisheries (McFarlane *et al.*, 2005). This is the basis for Canadian management assuming that 10% of the northern stock enters Canadian waters (DFO 2004). An experimental trawl survey in Canadian waters by McFarlane *et al.* (2005) and its analysis mentioned that their result supported this 10% annual migration rate. Their survey and analysis suggested abundances in July of 1997 and 1999: 88,843 tonnes (95% confidence interval (CI) as 66,947-136,288 tonnes) and 79,393 tonnes (95% CI : 64,656-100,972 tonnes) respectively. Corresponding estimations of the costal wide abundances are 917,855 tonnes for 1997 and 1,495,910 tonnes for 1999 in the 2007 stock assessment. This 10 % could still be arguable due to uncertainties associated with abundance estimations. However, under the dynamics of abundance and distribution changes of Pacific sardine under regime shifts, the static framework for fishing in Canadian water may overestimate the availability of fish in Canadian waters. If this is the case, it may lead overfishing in the future. Therefore an additional study is urgently required to foster sustainable development of the Pacific sardine fisheries.

A.3.4 Current management and research

Although the stock assessment model by Hill *et al.* (2006) did not include sea temperature driven components in a population dynamics model, the harvest guide line of Pacific Fishery Management Council (PFMC), which is the U.S. management body for Pacific sardine, includes consideration of sea temperature in fishing mortality for the Maximum Sustainable Level (MSY). The following two equations are currently adapted as the U.S. harvest guideline (HG)¹⁸;

$$\text{A.1} \quad \text{HG} = (\text{BIOMASS} - \text{CUTOFF}) \cdot \text{DISTRIBUTION} \cdot \text{FRACTION}$$

$$\text{A.2} \quad \text{FRACTION} = 0.25T^2 - 8.19T + 67.46$$

BIOMASS is the estimated biomass for this stock assessment year. CUTOFF is the minimum biomass allowed for fisheries and is set at 150,000 tonnes. This implies that fisheries will be closed if the biomass of sardine is below 150,000 tonnes. As in the previous section, DISTRUBUTION is a static constant number set as 87%. FRACTION is calculated from the running average sea-surface temperature (T) at Scripps Pier, La Jolla, California during the three (years) preceding fishing seasons (July-June). Jacobson and MacCall (1995) explored a stock-

¹⁸ See more details in Hill *et al.*, (2006)

recruitment model for Pacific sardine and found a significant relationship between the logarithm of recruitments per unit of spawning biomass and the average sea surface temperature (SST) in the three preceding fishing seasons (see Table A-1). They concluded that the MSY of Pacific sardine is less than or equal to zero when the mean three season SST falls below 16.3°C and increases when the mean three season SST rises. Equation A.2 for FRACTION reflects their study results as a minimized FRACTION at 16.47°C as 0.014.

FRACTION is restricted to between 5% and 15%. In 2007, T was used as 18.11 °C and FRACTION was calculated as 15%. Canadian management adapts these Equations and uses 10% for DISTRIBUTION. Currently, Mexico does not have a management procedure considering sea temperature to limit their catch.

Jacobson *et al.* (2005) developed a surplus production population dynamics model with environmental disturbances. He examined two environmental indicators to effect the MSY (as carrying capacity) of Pacific sardine, 1) sea surface temperature from Scripps Pier, La Jolla, and 2) spatial expansions of habitats of Pacific sardine. As an environmental indicator increased (temperature rise or habitat expansion), the MSY in his model, whereby the abundance of Pacific sardine increased. While his study does not cover the detailed mechanism of

environmental effects on the Pacific sardine stock, his model successfully showed the possibility of including environmental disturbances in population dynamics.

The number of studies exploring the detailed mechanism of the relationship between sea temperature and the abundance/distribution of the Pacific sardine is limited. Agostini *et al.* (2007) examined the relationship between the reproductive success of the Pacific sardine and zooplankton volume in the primary spawning ground off the California coast. Their study suggested that the predation of zooplankton, the abundance of which fluctuated based on sea surface temperature, would limit the survival rate of Pacific sardine larvae, and could thus induce dramatic fluctuations in the abundance of Pacific sardine. This is currently the only proposed detailed mechanism of environmental effects on fluctuations of Pacific sardine stocks. Other possible causes could be direct physiological effects on the growth or survival rate of Pacific sardine eggs or larvae by sea temperature. For instance, as mentioned in the life history section, hatching of Pacific sardine requires a relatively high temperature between 14 C° and 16 C°, and this might be one cause of fluctuations in abundance under the cold/warm regime shifts. Further research is required to reveal the relationship between sea temperature and the abundance/distribution of the Pacific sardine.

A.4 Ecological roles of Pacific sardine in the California Current Ecosystem

Growing concern over an ecosystem-based approach rather than a single species stock assessment in fishery management, coupled with the recognition of climate impact on fish resources, has drawn attention to the ecological roles or values of a single fish species in an ecosystem. Forage fish, like Pacific sardine, which is dominant in abundance in a marine ecosystem, are essential to the successful functioning of the food web in coastal upwelling regions through their dual role as both prey and predator. Pacific sardine certainly consumes substantial phytoplankton and zooplankton when their abundance is high, and it is prey for higher trophic level fish, birds and marine mammals. However, little is known about the ecological role of Pacific sardine in the CCE. Presently, only a few studies have been done to estimate and describe this role.

A.4.1 Pacific sardine as a predator and prey

The feed of the Pacific sardine is primarily phytoplankton and secondarily zooplankton. Lasker (1970) estimated the consumption of the Pacific sardine stock from individual fish energy consumption. He assumed Pacific sardine only feed on the secondary production and 10% primary production is accumulated into the secondary production. His conclusion was that the

secondary production in the CSS during 1932-34 was 45.4% of which the Pacific sardine stock required during that period.

All life stages of Pacific sardine in the CCE are vulnerable to a variety of predators CCE. Emmette *et al.* (2005) conducted predator surveys for Pacific sardine between 1999 and 2004. Their study confirmed Coho and Chinook are predators of the Pacific sardine, but could not quantify the effect of this predation of the Pacific sardine on the biomass of Coho and Chinook salmon. Orr *et al.* (2004) found that Pacific harbour seals are also consumers of Pacific sardine. These studies described the possible ecological roles of Pacific sardine in the CCE, but did not quantify the effects of Pacific sardine abundance on the abundance of predators.

Field *et al.* (2006) developed an ecological model of the Northern California Current system with data from literatures and quantified biomass flows associated with the Pacific sardine by using *Ecopath*© , an ecosystem modeling software package (Walters *et al.*, 1997). They evaluated the quantitative interaction of the Pacific sardine with four different prey groups - phytoplankton, micro-zooplankton, copepods and euphausiids - and 10 different predators - Pacific salmon, northern albacore, murrres, gulls, orcas, toothed whales, sea lions, fur seals and baleen whale) – as estimated biomass flows (see their estimation in Table A-2). Their modelled

biomass trend for Pacific sardine, however, did not synchronize well with the time sequence estimations of abundance under the current stock assessment. The fundamental mechanism of *Ecopath* is a trophic level interaction. The sudden changes of abundance in the Pacific sardine stock would be because of their physiological or egg/juvenile cannibalism phenomenon rather than because of trophic interactions. This may cause difficulties in tracing the abundance of Pacific sardine within the framework of *Ecopath*. Moreover, their model does not include consumption by humans (i.e., fishery). This also may have an effect on model estimations.

A.4.2 Ecological roles

Emmett *et al.* (2005) introduced the possibility of Pacific sardine as a “wasp-waist¹⁹” population which takes a critical role in the trophic dynamics of an upwelling ecosystem. Their wasp-waist mechanism is as follows. In upwelling ecosystems, the intermediate trophic level is dominated by small-forge pelagic fish species. In most cases, this dominant species is sardine or anchovy. Their abundance fluctuates dramatically over time because of food limitation from lower trophic levels, rather than predation pressures from upper trophic levels. As the result of massive changes in the abundance of a “wasp-waist” population, the entire food web is controlled from this intermediate trophic level, dominated by the Pacific sardine. This would

¹⁹Original concept was suggested by Cury *et al.*, (2000).

explain subsequent changes in the upper trophic level structure of the CCE, but there is no single study to confirm yet.

A.5 Concluding remarks

Understanding the variability in abundance and geographical distributions of the Pacific sardine will involve many complex elements, such as the biology, trophic interactions, and a variety of oceanographic conditions induced by cold-warm regimes. In past decades, research efforts have been devoted to understanding this complexity, yet, we still do not understand enough to draw a complete picture of the dynamics of the Pacific sardine stock. All we are sure of is that the warm and cold regime shifts in the CCE affect stock abundance and subsequently change geographical distribution. The warm regime increases abundance and expands the geographical distribution northward to Oregon, Washington and British Columbia. In contrast, the cold regime decreases abundance and limits the geographical distribution within southern California and Baja California. It is worth noting that – even though much recent scientific effort has been devoted to climate change, our ability to predict actual regime shifts is extremely limited (Mantua and Mote 2002). Considering this uncertainty, our ability to predict the abundance and geographical distribution of the Pacific sardine is not promising.

Table A-1 Estimated equilibrium spawning biomass and MSY for three preceding fishing seasons (July-June) from Hill *et al.*, (1999).

Mean three season SST °C	Equilibrium spawning biomass(1000 tonnes)	MSY (1000 tonnes)
16.5	700	9
17.0	2700	156
17.3	>4000	346

Table A-2 Estimated biomass flows associated with Pacific sardine by Field *et al.*, (2006). Share of preys shows share of biomass consumptions by Pacific sardine. The sum of four preys is 100%. Share of biomass taken by predators show share of biomass of Pacific sardine taken by predators.

Prey of Pacific sardine	Share of preys in the consumption (%)	Predator of Pacific sardine	Share of biomass taken by predators (%)
Phytoplankton	28.0	Pacific salmon	1.0
Micro zooplankton	2.0	Northern albacore	5.0
Copepods	40.0	Coastal sharks	5.0
Euphausiids	30.0	Common murre	0.1
		Gulls	0.1
		Orcas	0.5
		Toothed whales	5.0
		Sea lions	1.0
		Fur seals	1.0
		Baleen whales	9.0

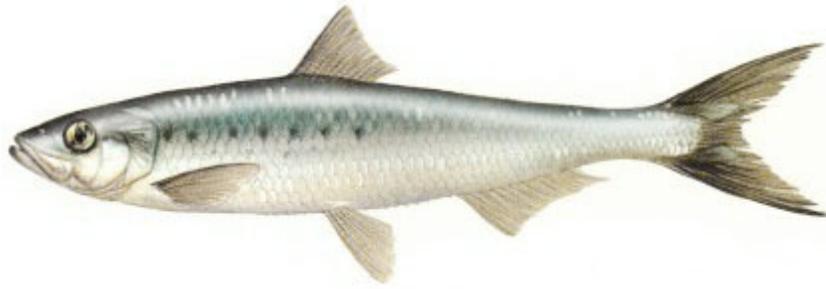


Figure A-1 Pacific sardine (from <http://bridgesdesign.net/sardineking/sardinespecs.html>).

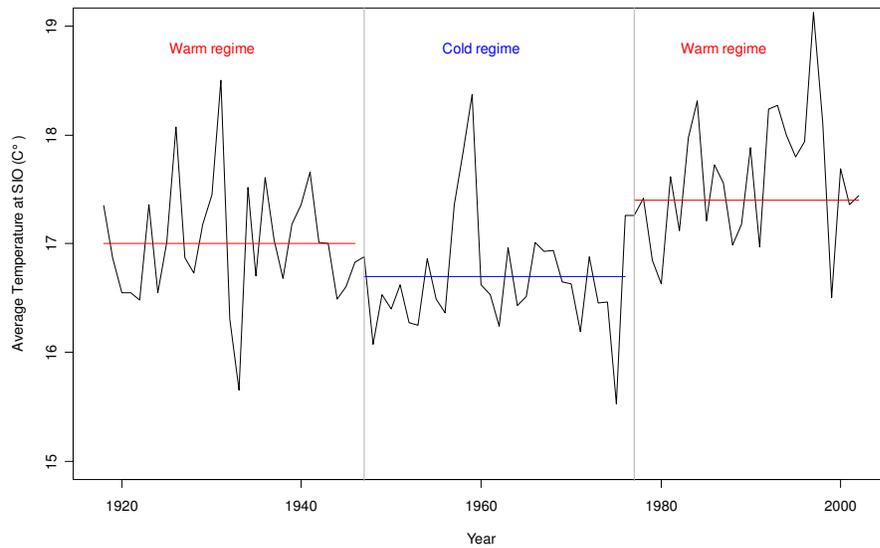


Figure A-2 Average temperature during July-June at Scripps Pier, La Jolla, California. This temperature is used as a proxy of the temperature at the CSS in the Pacific sardine management.

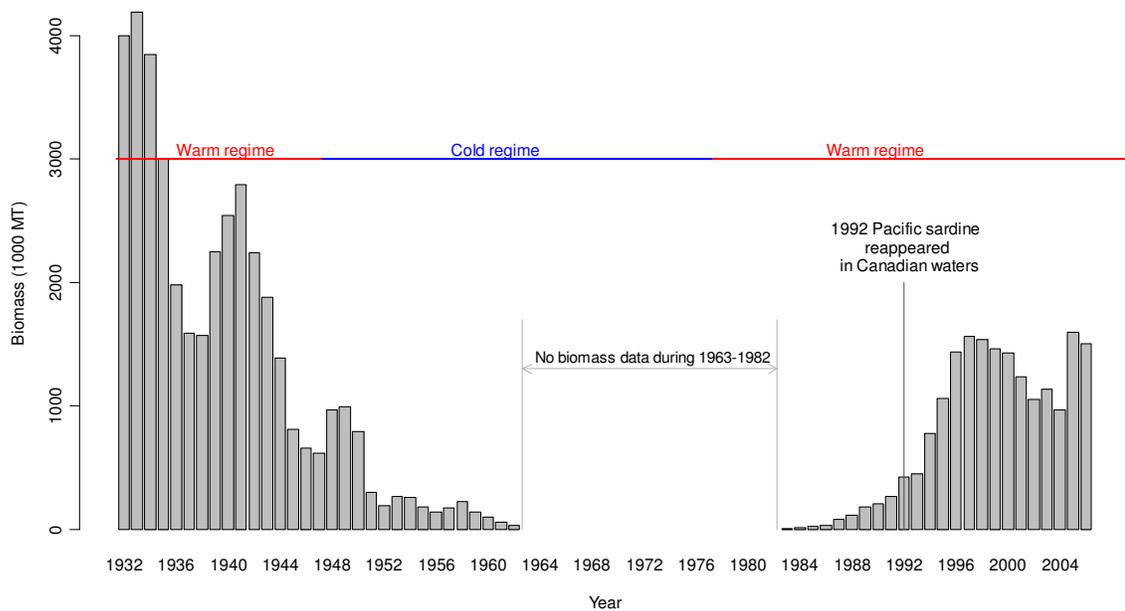


Figure A-3 Biomass changes of Pacific sardine (data from Hill *et al.*, 2007).

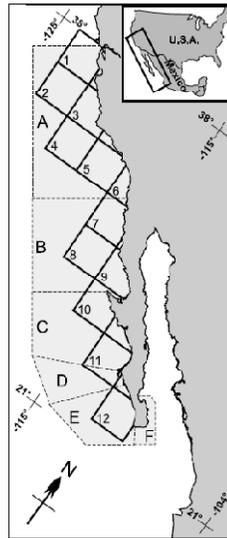


Figure A-4 Defined fishery areas off California and Baja-California from Rodríguez-Sánchez *et al.*, (2002). Areas: (A) California waters; (B) Mexican border to Punta Eugenia; (C) Punta Eugenia to Cabo San Lazaro; (D) Bahia Magdalena – Bahia Almejas – Bahia Santa Maria; (E) Punta Redonda to Cabo Falso; (F) Gulf of California West (Cabo Falso – Bahia de La Paz).

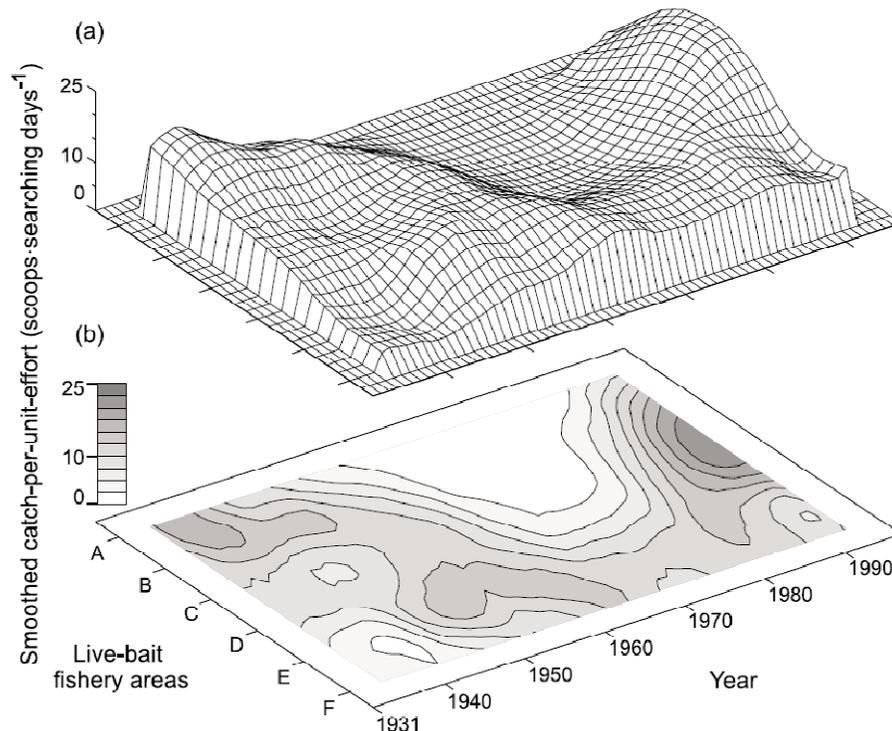


Figure A-5 Geographical variability of Pacific sardine CPUE along California and Baja California for the 67 year period from Rodríguez-Sánchez *et al.*, (2002). (a) A three-dimensional view of CPUE and (b) its projection in two dimensions. Areas A-F are corresponding in Figure 4.

Appendix A references

- Agostini, V. N., A. Bakun, and R. C. Francis. 2007. Larval stage controls on pacific sardine recruitment variability: High zooplankton abundance linked to poor reproductive success. *Marine Ecological Progress Series* 345: 237-244.
- Bakun, A., and S. J. Weeks. 2004. Greenhouse gas buildup, sardines, submarine eruptions and the possibility of abrupt degradation of intense marine upwelling ecosystems. *Ecology Letters* 7(11):1015-1023.
- Bureau of Marine Fisheries. 1945. Fish Bulletin No. 61. Results of Tagging Experiments in California Waters on the Sardine (*Sardinops caerulea*). Scripps Institution of Oceanography Library. *Fish Bulletin*: 61.
- Butler, J. L. 1987. Comparisons of the larval and juvenile growth and larval mortality rate of Pacific sardine and northern anchovy and implications for species interactions. Ph.D Thesis, University of California, San Diego, 240 pp.
- Chavez, F. P., J. Ryan, S. E. Lluch-Cota, and M. C. Niquen. 2003. From anchovies to sardines and back: Multidecadal change in the Pacific Ocean. *Science*, 299(5604):217-221.
- Culley, M. 1971. The pilchard; biology and exploitation. , 1st edition. Pergamon Press, Oxford, New York.
- Cury, P., A. Bakun, R. J. Crawford, A. Jarre, R. A. Quinones, L. J. Shannon, and H. M. Verheye. 2000. Small pelagics in upwelling systems: Patterns of interaction and structural changes in "wasp-waist" ecosystems. *ICES Journal of Marine Science* 57(3):603-618.
- DFO (Fisheries and Oceans Canada). 2004. Stock status report 2004/037. Report 037.
- Emmett, R. L., R. D. Brodeur, T. W. Miller, S. S. Pool, G. K. Krutzikowsky, P. J. Bentley, and J. McCrae. 2005. Pacific sardine (*Sardinops sagax*) abundance, distribution, and ecological relationships in the Pacific Northwest. *Reports of California Cooperative Oceanic Fisheries Investigations* 46:122.
- Felix-Uraga, R., V. M. Gomez-Munoz, C. Quinonez-Velazquez, F. N. Melo-Barrera, and W. Garcia-Franco. 2005a. On the existence of pacific sardine groups off the west coast of Baja

California and southern California. *Reports of California Cooperative Oceanic Fisheries Investigations* 45:146-151.

Felix-Uraga, R., C. Quinonez-Velazquez, K. T. Hill, V. M. Gomez-Munoz, F. N. Melo-Barrera, and W. Garcia-Franco. 2005b. Pacific sardine (*Sardinops sagax*) stock discrimination off the west coast of Baja California and southern California using otolith morphometry. *Reports of California Cooperative Oceanic Fisheries Investigations* 46:113-121.

Field, J. C., R. C. Francis, and K. Aydin. 2006. Top-down modeling and bottom-up dynamics: Linking a fisheries-based ecosystem model with climate hypotheses in the northern California current. *Progress in Oceanography* 68(2-4):238-270.

Field, J., and R. Francis. 2002. Cooperating with the environment: Case studies of climate and fisheries in the northern California current. *American Fisheries Society*, Bethesda MD.

Field, J. C. 2005. Application of ecosystem-based fishery management approaches in the northern California current. Ph.D dissertation the University of Washington, ProQuest Information & Learning, Ann Arbor MI.

Hare, S. R. and N. J. Mantua. 2000. Empirical evidence for North Pacific regime shifts in 1977 and 1989. *Progress in Oceanography* 47(2-4): 103-146.

Hart, J. L. 1937. A brief account of the life-history of the pilchard. B.C. Fisheries Department Report. p 50-56.

Hedgecock, D., E. S. Hutchinson, G. Li, F. L. Sly, and K. Nelson. 1989. Genetic and morphometric variation in the Pacific sardine, *Sardinops sagax caerulea* : Comparisons and contrasts with historical data and with variability in the northern anchovy, *Engraulis mordax*. *Fishery Bulletin* 87(3):653-671.

Herrick, J., Samuel.F., J. G. Norton, J. E. Mason, and C. Bessey. 2007: Management application of an empirical model of sardine-climate regime shifts. *Marine Policy* 31(1):71-80.

Hill, K. T., L. D. Jacobson, N. Lo, M. Yaremko, and M. Cege. 1999. Stock assessment of pacific sardine for 1998 with management recommendations for 1999. *California Department of Game and Fish, Report* 99-4.

Hill, K. T., N. C. Lo, B. J. Macewicz, and R. Felix-Uraga. 2007. Assessment of the Pacific sardine (*Sardinops sagax caerulea*) Population for U.S. management in 2006. Pacific Fishery Management Council, Portland, OR USA.

Hill, K. T., E. Dorval, N. C. Lo, B. J. Macewicz, C. Show. and R. Felix-Uraga. 2008. Assessment of the Pacific sardine (*Sardinops sagax caerulea*) Population for U.S. management in 2007. Pacific Fishery Management Council, Portland, OR USA.

Jacobson, L. D., S. J. Bograd, R. H. Parrish, R. Mendelsohn, and F. B. Schwing. 2005. An ecosystem-based hypothesis for climatic effects on surplus production in California sardine (*Sardinops sagax*) and environmentally dependent surplus production models. *Canadian Journal of Fisheries and Aquatic Sciences* 62(8):1782-1796.

Jacobson, L. D., and A. D. MacCall. 1995. Stock-recruitment models for pacific sardine (*Sardinops sagax*). *Canadian Journal of Fisheries and Aquatic sciences* 52(3):566-577.

Lasker, B. 1970. Utilization of zooplankton energy by a pacific sardine population in the California current. Pages 265 in Utilization of zooplankton energy by a pacific sardine population in the California current. Marine food chains. University of California Press, Berkeley.

Lo, N. C. H., B. J. Macewicz, and D. A. Griffith. 2005. Spawning biomass of pacific sardine (*Sardinops sagax*), from 1994-2004 off California. *Reports of California Cooperative Oceanic Fisheries Investigations* 46:93.

MacCall, A. 1979. Population estimates for the warning years of the Pacific sardine fishery. *Reports of California Cooperative Oceanic Fisheries Investigations* 18:136-148.

MacCall, A. 1990. Dynamic geography of marine fish populations. University of Washington Press, Seattle, WA (USA).

Mantua, N. 2004. Methods for detecting regime shifts in large marine ecosystems: A review with approaches applied to north pacific data. *Progress in Oceanography* 60(2-4):165-182.

Mantua, N., and P. Mote. 2002. Uncertainty in scenarios of human-caused climate change. American Fisheries Society, Bethesda MD

- McFarlane, G. A., J. R. King, and R. J. Beamish. 2000. Have there been recent changes in climate? Ask the fish. *Progress in Oceanography* 47(2-4):147-169.
- McFarlane, G. A., and R. J. Beamish. 2001. The re-occurrence of sardines off British Columbia characterizes the dynamic nature of regimes. *Progress in Oceanography* 49(1-4):151-165.
- McFarlane, G. A., J. Schweigert, L. MacDougall, and C. Hrabok. 2005. Distribution and biology of pacific sardines (*Sardinops sagax*) off British Columbia, Canada. *Reports of California Cooperative Oceanic Fisheries Investigations* 46:144.
- Miller, A. J., and N. Schneider. 2000. Interdecadal climate regime dynamics in the North Pacific Ocean: Theories, observations and ecosystem impacts. *Progress in Oceanography* 47(2-4):355-379.
- Minobe, S. 2000. Spatio-temporal structure of the pentadecadal variability over the north pacific. *Progress in Oceanography* 47(2-4):318-408.
- Norton, J. G., and J. E. Mason. 2005. Relationship of California sardine (*Sardinops sagax*) abundance to climate-scale ecological changes in the California current ecosystem. *Reports of California Cooperative Oceanic Fisheries Investigations* 46:83-92.
- Orr, A. J., A. S. Banks, S. Mellman, H. R. Huber, R. L. DeLong, and R. F. Brown. 2004. Examination of the foraging habits of pacific harbor seal (*Phoca vitulina richardsi*) to describe their use of Umpqua River, Oregon, and their predation on salmonids. *Fishery Bulletin* 102(1):108-117.
- Parrish, R. H., R. Serra, and W. S. Grant. 1989. The monotypic sardines, sardina and sardinops: Their taxonomy, distribution, stock structure, and zoogeography. *Canadian Journal of Fisheries and Aquatic Sciences* 46(11):2019-2036.
- PFMC (Pacific Fishery Management Council). 2007 <http://pcouncil.org/cps/cpsback.html> as of Janaury 12, 2010.
- Rodriguez-Sanchez, R., D. Lluch-Belda, H. Villalobos, and S. Ortega-Garcia. 2002. Dynamic geography of small pelagic fish populations in the California current ecosystem on the regime time scale. *Canadian Journal of Fisheries and Aquatic Sciences* 59(12):1980-1988.

Schweigert, J. F. 2002. Update COSEWIC status report on the pacific sardine *Sardinops sagax* in Canada, in COSEWIC assessment and update status report on the pacific sardine *Sardinops sagax* in Canada. Committee on the Status of Endangered Wildlife in Canada, Ottawa.

Schweigert, J. F., G. A. McFarlane, and Canadian Science Advisory Secretariat. 2002. Stock assessment and recommended harvest for pacific sardine in 2002. :12.

Vrooman, A. M. 1964. Serologically differentiated subpopulations of the Pacific sardine, *Sardinops caerulea*. *Journal of the Fisheries Research Board of Canada* 21(4):691-701.

Walters, C., V. Christensen, and D. Pauly. 1997. Structuring dynamic models of exploited ecosystems from trophic mass-balance assessments. *Reviews in Fish Biology and Fisheries* 7(2):139-172.

Ware, D. M. 2004. Life history of pacific sardine and a suggested framework for determining a B.C. catch individual catch shares . Canadian Stock Assessment Secretariat Research Document 99/2004

APPENDIX B: BASIC ECONOMICS OF PACIFIC SARDINE FISHERIES

B.1 Introduction

The objective of this appendix is to provide background information of this dissertation. To do so, this appendix first gives an overview of Pacific sardine resources and fisheries. Secondly, bioeconomic models approach and game theory are introduced as a tool to analyze transboundary fisheries resources.

A fishery is composed of the interaction between fish and humans through fishing. Since fish are a renewable natural resource, if we embrace conservation to maintain the size of parental fish stocks, fisheries resources can, in theory, bring recurring benefits to society. Fisheries provide benefits as food sources and supports employment in the economy. However, there are inevitably challenges in fisheries management, due to uncertainties and compounded complexities inherent in a fishery system, to maximizing these benefits and ensuring that they are sustainable. Examples of such uncertainties and complexities include unanticipated marine environmental variability and errors in stock assessments (Clark 2006).

The key to fisheries resource management lies in how we manage and regulate fishing activities. Economic analysis is an indispensable part of the process, and has multiple roles. First, economics can be used to study the use of scarce resources, which aptly applies to fisheries

resources (Hannesson 1993). Economic analysis of fisheries suggests that fishing can be sustainable and offer maximum economic benefits by studying the costs incurred by fishers. In other words, the economic analysis of a fisheries resource can help determine the appropriate scale of fishing activity possible to achieve a specific management goal. Second, in the past century, excessive fishing, on a global scale, motivated by fishers' economic interests has resulted in overfishing and has moved fisheries away from sustainability with the result that benefits are not being maximized. Without economic analyses, fisheries management will not be able to design appropriate economic incentives and regulate excess fishing effort.

Throughout the last century, Pacific sardine (*Sardinops sagax*) in the California current ecosystem (the CCE) has exhibited extreme sensitivity in its abundance and distribution in the face of climate regime shifts. Warm regimes enhanced the abundance of Pacific sardine and expanded its distribution. Cold regimes lessened abundance and restricted distribution. Fisheries management of the Pacific sardine had been complicated by this variability. Between the late 1940s and the 1970s, a cold regime shift in the CCE, combined with overfishing, resulted in the collapse of Pacific sardine resources. As abundance decreased, the spatial availability of the resource to commercial fisheries shifted from having a wide range - Canada (British Columbia), the U.S. (Washington, Oregon, California) and Mexico (Baja California), to

a limited range - southern California and Mexico. Eventually, direct fisheries for Pacific sardine in the U.S. were closed in 1973. Since the 1980s, a warm regime shift in the California current has restored a favourable environment for Pacific sardine (Herrick *et al.*, 2007). With conservation efforts, the abundance of the Pacific sardine recovered to the 1940s level, and the fish reappeared in the waters of the Northwest U.S. (Oregon and Washington) and Canada. In 1986, direct fisheries for the Pacific sardine were reopened in U.S. Canada removed Pacific sardine from its endangered species list and reopened an official fishery in 2003. Now, economic interest in Pacific sardine is rising among the three countries. Due to the focus on biological uncertainties in the management of the Pacific sardine, economic analyses have not previously been applied to Pacific sardine.

B.2 Overview of the Pacific sardine resource and fisheries

B.2.1 Pacific sardine resource

Pacific sardine in the California current system is a pelagic fish with tight schooling behavior. Currently, three substocks of Pacific sardine are recognized (Felix-Uraga *et al.*, 2005a; Felix-Uraga *et al.*, 2005b). These substocks are 1) the northern substock, whose distribution ranges from northern Baja California to south eastern Alaska; 2) the southern substock whose annual

distribution ranges from Baja California to southern California; and 3) the Gulf of California substock, which is distributed within the Gulf of California. Extensive fisheries in the U.S. and Canada occur only on the first substock, which spends time within the exclusive economic zones (EEZs) of Mexico, Canada and the U.S. due to its annual migration. Accordingly, this appendix will focus only on the northern substock.

The abundance and distribution of Pacific sardine is extremely sensitive to sea surface temperature changes in the California current system (Hill *et al.*, 2006). Mirroring abundance, historical landings of the Pacific sardine also exhibited extreme variability under regime shifts in the California current system. Historically, until the middle of the 1940s, the Pacific sardine resource fueled the largest fisheries in North America with an annual catch of 500,000 tonnes and peaking at 700,000 tonnes. This fishery operated along the coast off British Columbia, Canada (BC), Oregon (OR), Washington (WA), California (CA) and Baja California, Mexico (MX). Depletion of the Pacific sardine stock began in 1945. Between the late 1940s and the 1970s, a cold regime shift in the California current system, combined with excess fishing effort, resulted in the collapse of the Pacific sardine resource, with annual total landings as low as 5,000 tonnes. As a result, a moratorium on the U.S. Pacific sardine fishery was called in 1973. In the mid 1980s, a warm regime shift in the California current system, along with fisheries

closures, allowed for the Pacific sardine resource to recover rapidly. From 1983 to 2005, the age 1+biomass of Pacific sardine expanded approximately ten times from 15,395 tonnes in 1983 to 1,503,871 in 2005 (Figure B-1(a)). Total coast-wide landings increased rapidly beginning in the early 1990s (Figure B-1(b)) and have reached over 10,000 tonnes annually since 1997. In 2005, total landings were 152,852 tonnes, the highest recorded since the recovery of the Pacific sardine resource.

B.2.2 Pacific sardine fisheries and markets

Pacific sardine fisheries are operated by three countries, Canada, the U.S. and Mexico. In all countries, the Pacific sardine fisheries are mainly conducted by purse seine vessels²⁰, which use round-haul nets to catch a variety of schooling aquatic resources including mackerel, anchovy, tuna, herring and market squid. Pacific sardine fisheries are, therefore, always part of a multispecies fishery and landings of the Pacific sardine are affected by the economic value and availability of additional species.

Because of its confidential nature, it is hard to get accounting data for purse seine fishery operations in the three countries so available information is limited. A typical set of a U.S.

²⁰ The experimental Canadian fishery is exploring the possibilities of alternative gears (e.g., longline, trap net), but purse seines still dominate Pacific sardine fisheries in the three nations.

purse seine vessel catches around 35-40 tonnes, and one or two successful sets fill a hold for a trip (Goblirsch and Theberge 2008). Nevárez-Martínez (1999) described the catch per trip for a typical purse seine vessel in the Mexican Pacific sardine fisheries in the Gulf of California as 70 tonnes. This Mexican fishery, however, targets the Gulf of California substock, not the northern substock. A typical Mexican purse seine vessel in the Gulf of California spends 28% of gross earning for crew share (Nevárez-Martínez *et al.*, 1999). Ishimura *et al.* (2004) estimated 29% expenditure of gross earnings for crew share for a typical mid-water trawling vessel in the U.S. West coast. Therefore, around 28% of the gross earnings would be a good proxy for crew payment for U.S. purse seiners. This information infers comparable Pacific sardine operations in the U.S. and Mexico. In the U.S. Pacific sardine fisheries, spotter airplanes are often employed, and spotter plane pilots take up to about 10-15% of gross earnings (Washington Department of Fish and Wildlife 2007).

Catch is processed in onshore facilities in ports. Processors in Canada and the U.S. process Pacific sardine for four uses, 1) direct human consumption; 2) aquaculture feed; 3) commercial fishery bait and 4) sport fishery bait (Pacific Fishery Management Council 2007). The majority of Pacific sardine catch goes for reduction fisheries, such as aquaculture feeding and bait for other commercial fisheries (e.g., tuna longline fisheries). Given the homogeneity of producers

and target markets, the U.S. and Canadian markets for reduction fisheries can be considered as an integrated market for North America. Only a small portion of the catch goes for direct human consumption, mainly in Japan. The ex-vessel price per pound has stayed around \$0.04-0.06 for the past several years. Recently, the industry has had success expanding the bait/aquaculture feed market in Japan, as well as in developing a new market for direct human consumption in Europe. Since the world market for reduction fisheries has a variety of substitute species (e.g., anchovies) and low unit ex-vessel prices, sardines for direct human consumption generally have higher unit prices. Therefore, additional marketing efforts toward direct human consumption of Pacific sardine would generate further economic incentives in Pacific sardine fisheries.

B.2.3 U.S. management

Among the three states within the U.S., three sectors can be identified, 1) Southern California (S.Cal); 2) Northern California (N.Cal); and 3) OR & WA. Each sector operates with an unique harvesting schedule. The fishing season for Pacific sardine in S.Cal starts in January and continues throughout the year. The N.Cal fishery typically starts in August, but is influenced by the availability of market squid, which has a higher market value. The OR and WA fishery only harvests between June and October. Vessels landing less than five metric tonnes of

coastal pelagic species²¹ per trip in S.Cal are exempt from limited entry licenses and operate as an open access fishery until the temporal/spatially allocated individual catch shares are filled. Vessels operating in N.Cal, OR and WA are required to have individual state permits (Pacific Fishery Management Council 2007).

Prior to 2006, the geographical allocations of the coast-wide harvest quota give 2/3 of the total to S.Cal fisheries (around Point Arena, CA) and 1/3 to N.Cal, OR, and WA fisheries. Since 2006, a new seasonal allocation scheme has been implemented rather than this geographical one, giving 35% of the harvest guideline (HG), which is based on stock abundance and sea temperature, to the January harvest, allocating 40% of HG (and any remaining allocation from January) in June and allocating the last 25 % of HG (and any remaining allocation from June) in September (Wiedoff and Smith 2006). These temporal allocations help to ensure that each sector adjusts to their unique harvest season and fishing opportunities.

B.2.4 Canadian management

Since the Pacific sardine resource disappeared from Canadian waters in the late 1940s, there were no direct fisheries for the Pacific sardine in Canadian waters for a significant period. In

²¹ Other coastal pelagic species include Pacific mackerel (*Scomber japonicas*), jack mackerel (*Trachurus symmetricus*), market squid (*Loligo opalescens*) and northern anchovy (*Engraulis mordox*).

1987, the Pacific sardine was listed as a species of concern by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) and direct commercial harvest was legally prohibited (Schweigert *et al.*, 2002). As the range of the resurgent northern stock expanded into B.C. between 1996 and 2001 there was a limited experimental harvest of the Pacific sardine. Both the success of the experimental harvest and the delisting of the Pacific sardine as a species of concern in 2002 led to the officially reopening of the Pacific sardine fishery in 2003. The fishery was developed under the New and Emerging Fisheries Policy of Canada. Currently, 25 purse seine vessels are operating around Vancouver Island and fisheries managers are studying the feasibility of using alternative gear (i.e., longline, trap net) (Fisheries and Oceans Canada 2004). The increased abundance of the Pacific sardine resource has brought new business opportunities to fisheries and associated industries in BC.

B.2.5 Mexican management

Although Pacific sardine fisheries management in Canada and the U.S. is well-documented, information pertaining to the Mexican sardine fishery is limited. The annual harvest for the Pacific sardine fishery in Mexico is regulated by a minimum legal size requirement of a fish length larger or equal to 165mm for landing. Other than this regulation, there is are no individual catch shares regulations for the Mexican fishery. The fishery is part of a multispecies

operation that also includes herring and mackerel (Hill *et al.*, 2007). In addition, the Mexican sardine fishery in Baja California may be landing several different sardine stocks while Canada and U.S. are exclusively landing the northern stock. It could therefore be a challenge to integrate the Mexican Pacific sardine fishery into an international management framework with the U.S. and Canadian Pacific sardine fisheries.

B.2.6 Dynamic transition of participants for the Pacific sardine fisheries

Due to dramatic changes in distribution, the relative scale of participation in the Pacific sardine fishery by the three nations has changed over the decades. This has resulted in a dramatic transition between new and existing resource users. The annual distribution of the Pacific sardine resource during cold regimes (late 1940s-early 1970s) was limited to S.Cal and Baja California, Mexico. As the resource was replenished during the warm regime that began in the 1970s, the annual distribution of Pacific sardine expanded further northward into N.Cal, OR, WA and BC. This distribution changes brought new fisheries opportunities in OR, WA and BC. There are two potential sources of conflict in the use of the Pacific sardine resource. First, there is an international conflict between pre-existing Pacific sardine fisheries in the U.S/Mexico and an emerging Pacific sardine fishery in Canada. Figure B-2 shows the changes in landing share for the three countries since 1983. Although the Canadian catch started increasing when the

direct fishery was reopened in 2003, Canada's share of the landings does not appear to be large (2 to 3 % of the total coast-wide landings). This is because of the limited market and processing capacity for Pacific sardine in Canada. DFO aims to allocate 10 % of the coast-wide ABC to Canadian fisheries, which reflects the estimated share of the annual distribution of Pacific sardine in Canadian waters (Fisheries and Oceans Canada 2004). Increased migration of Pacific sardine into Canadian waters, as well as setting up processing facilities and the development of markets would motivate Canadian fisheries to expand their operations. Secondly, there is a conflict in the Pacific sardine resource use within the U.S. Two groups of stakeholders in the U.S. fishery are involved in management. These are 1) the pre-existing sardine fishery in S. Cal; and 2) the new sardine fisheries in N.Cal, OR and WA, the latter being the result of the northward expansion of the Pacific sardine stock. Since 1998, the share taken by new resource users has increased dramatically and has reached 65% of the total landings in the U.S. This domestic allocation also reflects the northward distribution changes of the Pacific sardine stock.

In sum, in both cases, impending conflicts come from the time variant/asymmetric share of the Pacific sardine resource under cold/warm regimes in the California current system. The current warm regime continues to induce drastic changes in the abundance and distribution of the Pacific sardine resource (Field and Francis 2002) and could continue to induce transitions in the structure of Pacific sardine resource use. While the U.S. domestic allocation is governed by

decisions by the Pacific Fisheries Management Council, competitive management over Pacific sardine resources by three independent countries could lead to overexploitation of this resource.

A game theoretic analysis of this fish resource, based on a bioeconomic analysis, will model possible economic and biological outcomes that result from various strategic interactions between the three countries, and will be an essential tool in exploring optimal management policies for the Pacific sardine resource.

B.3 Bioeconomic analysis of fisheries resources

The three fundamental elements of a fishery system are that 1) fish are a renewable resource; 2) the market provides the catch to consumers as food sources and the fishers receive earnings for their harvest; and 3) fisheries are an economic activity by which fishers harvest fish resources.

A fishery system is dynamic with these three elements interacting together. Fisheries management aims to ensure sustainability and the maximum benefits to society from fisheries resources by regulating current and future fishing activity. Bioeconomic analysis is a tool that provides information on the potential consequences of management decisions regarding fisheries policies by simulating these dynamic interactions.

B.3.1 Fisheries resources

A prominent feature of fisheries resources is their renewability. Renewability means that fisheries resources have regenerative capacity given enough abundance (or the size of parental stock) (Aguero and Zuleta 1994), which comes from two biological processes, a) individual fish growth; and b) reproduction (or recruitment). Both fish growth and reproduction enhance the abundance of a stock, and contribute to current and future catches. To achieve sustainable fisheries and ensure the flow of benefits from fisheries resources in the future, management must maintain stock abundance.

B.3.2 Market

Another feature of fisheries resources, *scarcity*, originates in the market. *Scarcity* is the basis of the market economy. Goods and services are scarce because of limited availability (Hannesson 1993). Under a market economy, when demand exceeds supply, the unit price of goods and services increases. Alternatively, if supply (or production) exceeds demand, then the unit price of goods and services decreases. In the case of fisheries resources, supply is limited due to limited stock abundance and the production (catch) abilities of fisheries industries. Thus, the price of fish reflects increasing or decreasing scarcity of the fisheries resource. The price of the fish is a primary economic incentive for fishers.

B.3.3 Fishery

A fishery is an economic activity for fishers and also provides a significant food source to society. By using production capital (e.g., fishing vessels) and labour, fishers extract (catch) fisheries resources and sell them at markets. The aim of fishers is to maximize their return on capital and labour investments. Therefore, potential economic return is an incentive motivating fishers to operate. How these economic incentives are structured is important in fisheries management.

B.3.4 Fisheries bioeconomic model

The fisheries bioeconomic model is a tool used to integrate economic (market) and biological (renewable) processes in the fishery. The model consists of three main components: a fish population dynamic model as a biological component; a market model for the catch as an economic component; and a production model for fishing vessels. Using a bioeconomic model, one can simulate the biological responses of the resource to different management decisions and the subsequent economic performance of the fishery.

Fisheries bioeconomic was developed by a Canadian economist, H. S. Gordon, and published in his seminal paper in 1954. During the 1970s and 1980s, C. W. Clark and G. Munro (Clark and Munro 1978; Clark, Clarke and Munro 1979; Munro 1979) extended the analysis by introducing a variety of financial and economic theories (e.g., game, capital and investment theory). The number of applications for practical management, however, is limited. Furthermore, most fisheries management still relies on estimated catch levels to evaluate fishing policies, rather than economic consequences.

B.3.4 Application of the fisheries bioeconomic model to Pacific sardine fisheries

The overexploitation of fisheries resources is a critical issue in fisheries management. In the last century, excess fishing motivated by fishers' economic incentives has degraded fisheries resources all around the world. The Pacific sardine was no exception. Excess fishing during 1940-50s accelerated the collapse of the Pacific sardine resource, a fishery that was already degraded by the unfavorable cold regime of the California current ecosystem. Fisheries bioeconomic analysis is the only available tool to analyze both the economic and biological performance of Pacific sardine fisheries and to reveal the economic incentives which could potentially lead to tragic consequences, given biological uncertainties caused by unpredictable climate regime changes.

B.4 Management and economic analysis of a transboundary fish stock

During the 1970s, ongoing discussions at the United Nations Convention on the Law of the Sea resulted in most of the continental shelves being incorporated into the 200 nautical mile Exclusive Economic Zone (EEZ) of coastal nations. Nevertheless, the inclusion of continental shelves within countries' EEZ failed to achieve sole ownership for shared fish stocks, i.e., those that migrate or are distributed beyond two or more countries' EEZ and/or the high seas. A transboundary fish stock is one type of shared fish stock which can be found in the EEZ of more than one country. Pacific sardine is considered a transboundary fish stock in the California current system, as it migrates between three jurisdictions - Canada, the U.S. and Mexico.

B.4.1 Uniqueness of a transboundary fish

A common characteristic of transboundary fish stocks is that one country's fishing activities affects the potential harvest opportunities of other countries (Munro 2002). This means that one participant's economic return from a transboundary fish stock is dependent on fishing activities of other participants. The dynamic externality of a transboundary fish stock (e.g., collapse of stock) therefore arises from the competitive exploitation of a single fish stock by more than one country. This is also often referred to as non-cooperative exploitation. Sumaila (1999) stated

that non-cooperative exploitation will lead to suboptimal outcomes even if each country behaves in a rational manner, whereas cooperative exploitation, which aims to maximize the joint benefit of all participant countries, will provide a better solution for most shared fish stocks.

B.4.2 Game theory – a tool to analyze a transboundary fish stock

Game theory is a tool that undertakes to analyze strategic interactions between multiple players, for example cooperative and non-cooperative strategies among participants. It has been widely applied to analyze transboundary fisheries resources (e.g., Munro 1979; Munro 1990; Sumaila 1995; Armstrong and Sumaila 2001; Lindroos 2004a). A game for fisheries consists of 1) a set of agents (countries); 2) a set of strategies (exploitation policies); and 3) a set of payoffs (benefits) from a given strategy. Cooperative exploitation includes binding agreements among countries. Here, countries aim to maximize the joint benefit from the fisheries resource. Outcomes of cooperative exploitation of fisheries resources would be equivalent to that by a sole owner. In non-cooperative exploitation, each country is assumed to act with rational self-interest to accomplish the maximization of their own benefits from the resource.

Munro (1990) analyzed three non-cooperative exploitation scenarios over a transboundary fish stock under assumptions of invariant distributions among countries and a unified market for catch.

- a) a country with the higher operating cost will tend to withdraw from the fishery;
- b) a country with the greatest fishing efficiency tends to dominate the fishery;
- c) where catch per unit effort (CPUE) is inelastic to the abundance of fish, non-cooperative exploitation will fail to maximize benefit from a transboundary fish stock .

His analysis encourages cooperative exploitation of a transboundary fish stock. Success in the management of a transboundary fish stock relies on cooperative exploitation with binding agreements among the participating countries. How the players manage the fisheries resource and how they share this fish stock are both important (Hannesson 2004; Munro *et al.*, 2004).

Two critical elements of fisheries management need to be addressed in binding agreements.

First, the size of the fish stock that will be left to ensure the reproduction of future catch (escapement biomass) must be determined. This, of course, also defines the size of the permitted total catch (e.g., Allowable Biological Catch, ABC). Second, each country's share of the permitted catch needs to be set. This has often been done by considering the catch history of participating countries or the spatial distribution (or migration pattern) of a transboundary fish stock. If all or most of the participating countries understand that the benefits from cooperative

exploitation are superior to non-cooperative use, they can enter into a binding agreement for cooperative exploitation.

B.4.3 Coalition game – analysis of a transboundary fish stock

If there are more than two players in the game, then partial cooperation among participants needs to be recognized. A coalition game allows such partial cooperative exploitation, where a coalition can exist having a number of participants less than the total number in the fishery. This model has been applied to analyze various shared fish stocks (e.g., Kaitala and Lindroos 1998; Li 1998; Lindroos and Kaitala 2000; Pintassilgo 2003; Lindroos 2004a,b; Kronbak and Lindroos 2006 and 2007).

A coalition game model for a transboundary fish stock consists of three elements, 1) a set of countries for each coalition; 2) a set of strategies; and 3) for each country, preferences over the set of all strategies of all coalitions of which the country is a member. In a coalition game, as well as in other cooperative games, participants deviate from binding agreements if outcomes are not optimal for them. The analysis of stability in each possible coalition is done by examining outcomes of games and the distribution of outcomes among participants within a coalition by using the characteristic function game form, which associates benefits and yields

from each coalition with various sharing rules (e.g., core, shapely value) within a coalition (Kronbak and Lindroos 2007).

B.5 Concluding remarks

There is, as yet, no official cooperative management agreement in place among the three countries currently fishing the Pacific sardine. Conducting a bioeconomic analysis of Pacific sardine will reveal economic and biological consequences of different fishing and management policies under uncertainties of abundance and distribution. Although several challenges exist to the execution of a bioeconomic analysis on Pacific sardine resources, knowledge of potential economic and biological outcomes for the three countries from various fishing policies, including non-cooperative strategies, would be beneficial and it is necessary to encourage the establishment of such agreements.

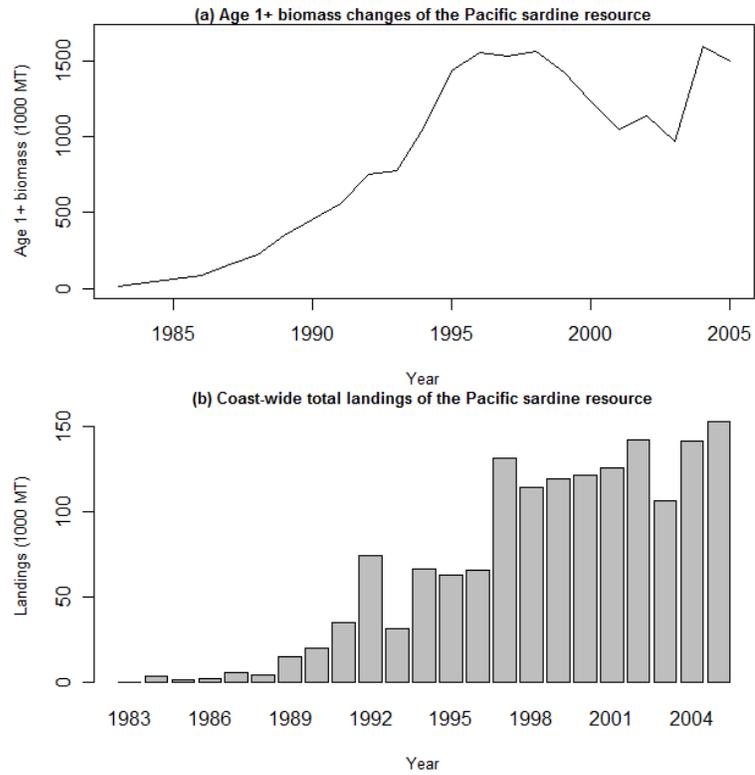


Figure B-1 (a) Age 1+ biomass change of the Pacific sardine resource between 1983 and 2005. (b) Coast-wide landings of the Pacific sardine resource between 1983 and 2005 (data from Hill *et al.*, 2007).

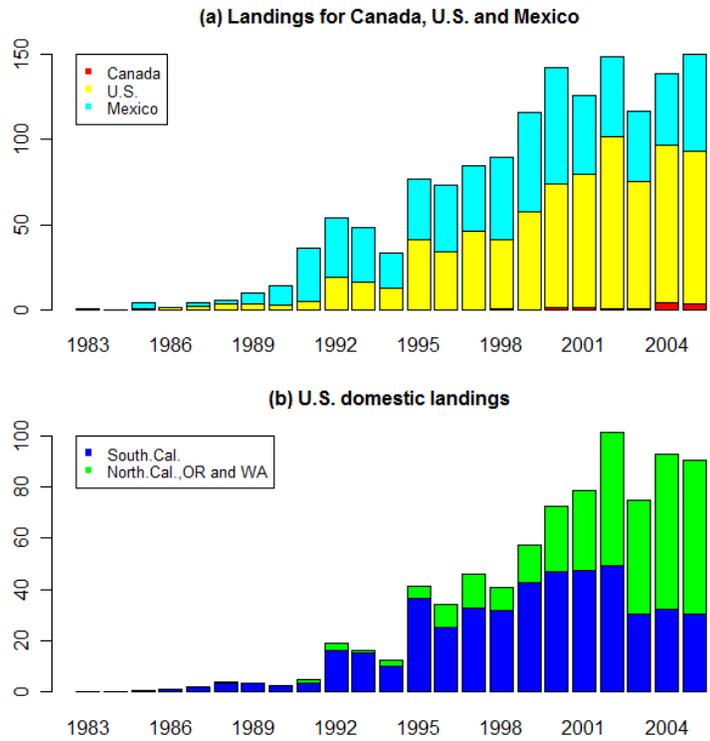


Figure B-2 Landings change of the Pacific sardine resource among different sectors, a) Canada, U.S. and Mexico, and b) U.S. domestic (data from Hill, 2007).

Appendix B references

Aguero, M., and A. Zuleta. 1994. Management options for transboundary stocks: The peruvian-chilean pelagic fishery. Pages 66-78 in E. A. Loayza, editor. *Managing fishery resources: Proceedings of a symposium co-sponsored by the world bank and peruvian ministry of fisheries held in lima, peru, June 1992*. World Bank Discussion Papers, no. 217. Fisheries Series; Washington, D.C.; World Bank,.

Armstrong, C. W., and U. R. Sumaila. 2001. Optimal allocation of TAC and the implications of implementing an ITQ management system for the north-east arctic cod. *Land Economics* 77(3):350-59.

Clark, B. M. 2006. Climate change: A looming challenge for fisheries management in southern africa. *Marine Policy* 30(2):84-95.

Clark, C. W., F. H. Clarke, and G. R. Munro. 1979. The optimal exploitation of renewable resource stocks: Problems of irreversible investment. *Econometrica* 47(1):25-47.

Clark, C. W., and G. R. Munro. 1978. Renewable resource management and extinction: Note. *Journal of Environmental Economics and Management* 5(2):198-205.

Felix-Uraga, R., V. M. Gomez-Munoz, C. Quinonez-Velazquez, F. N. Melo-Barrera, and W. Garcia-Franco. 2005a. On the existence of pacific sardine groups off the west coast of baja California and southern California. *Reports of California Cooperative Oceanic Fisheries Investigations* 45:146-151.

Felix-Uraga, R., C. Quinonez-Velazquez, K. T. Hill, V. M. Gomez-Munoz, F. N. Melo-Barrera, and W. Garcia-Franco. 2005b. Pacific sardine (*sardinops sagax*) stock discrimination off the west coast of baja California and southern California using otolith morphometry. *Reports of California Cooperative Oceanic Fisheries Investigations* 46:113.

Field, J., and R. Francis. 2002. Cooperating with the environment: Case studies of climate and fisheries in the northern California current. *American Fisheries Society* 54:10

Fisheries and Oceans Canada (DFO). 2004. Stock status report 2004/037. Report 037.

Goblirsch, G. and S. Theberge. Oregon sea grant - getting to know Oregon's commercial fisheries: Purse seiners, Available: <http://seagrant.oregonstate.edu/sgpubs/onlinepubs/g03011.html>. (2/14/2008).

Hannesson, R. 1993. Bioeconomic analysis of fisheries. Fishing News Books, Oxford (UK).

- Hannesson, R. 2004. Sharing the herring: Fish migrations, strategic advantage, and climate change. Institute for Research in Economics and Business Administration, Report 27, .
- Herrick, J.,S.F., J. G. Norton, J. E. Mason, and C. Bessey. 2007. Management application of an empirical model of sardine-climate regime shifts. *Marine Policy* 31(1):71-80.
- Herrick, J.,S.F.and D. Dealy. 2005. Economic Status of Washington, Oregon, and California CPS Fisheries in 2004. In Status of the CPS. Pacific Fishery Management Council, 2130 SW Fifth Ave., Suite 224, Portland, Oregon 97201.
- Hill, K. T., N. C. Lo, B. J. Macewicz, and R. Felix-Uraga. 2007. Assessment of the Pacific sardine (*sardinops sagax caerulea*) Population for U.S. management in 2006. Pacific Fishery Management Council, Portland, OR USA.
- Hill, K. T., E. Dorval, N. C. Lo, B. J. Macewicz, C. Show. and R. Felix-Uraga. 2007. Assessment of the Pacific sardine (*sardinops sagax caerulea*) Population for U.S. management in 2008. Pacific Fishery Management Council, Portland, OR USA.
- Ishimura,G., D.D. Huppert, and A. E. Punt. 2004 “Can we stabilize fisheries’ benefits from a fluctuating stock? The bioeconomic assessment of the Pacific whiting fishery in *Proceeding of Institute of International Fisheries Economics and Trade* 2004.
- Kaitala, V., and M. Lindroos. 1998. Sharing the benefits of cooperation in high seas fisheries: A characteristic function game approach. *Natural Resource Modeling* 11(4):275-99.
- Kronbak, L. G., and M. Lindroos. 2006. An enforcement-coalition model: Fishermen and authorities forming coalitions. *Environmental and Resource Economics* 35(3):169-194.
- Kronbak, L. G., and M. Lindroos. 2007. Sharing rules and stability in coalition games with externalities. *Marine Resource Economics* 22(2):137-154.
- Li, E. 1998. Cooperative high-seas straddling stock agreement as a characteristic function game. *Marine Resource Economics* 13(4):247-58.
- Lindroos, M. 2004a. Restricted coalitions in the management of regional fisheries organizations. *Natural Resource Modeling* 17(1):45-69.
- Lindroos, M. 2004b. Sharing the benefits of cooperation in the Norwegian spring-spawning herring fishery. *International Game Theory Review* 6(1):35-53.

- Lindroos, M., and V. Kaitala. 2000. Nash equilibria in a coalition game of the Norwegian spring-spawning herring fishery. *Marine Resource Economics* 15(4):321-39.
- Munro, G. R. 1979. The optimal management of transboundary renewable resources. *Canadian Journal of Economics* 12(3):355-76.
- Munro, G. R. 1990. The optimal management of transboundary fisheries: Game theoretic considerations. *Natural Resource Modeling* 4(4):403-26.
- Munro, G. R. 2002. The optimal management of transboundary renewable resources. *Fisheries Economics: Collected Essays. Volume 2*:63-84.
- Munro, G., A. Houtte, R. Willmann, 2004. The conservation and management of shared fish stocks: Legal and economic aspects. *FAO Fisheries Technical Paper* 465
- Nevárez-Martínez, M. O., E. A. Chávez, M. A. Cisneros-Mata, and D. Lluch-Belda. 1999. Modeling of the pacific sardine *sardinops caeruleus* fishery of the gulf of California, Mexico. *Fisheries Research* 41(3):273-283.
- Pacific Fishery Management Council. 2007. Status of the Pacific Coast Coastal Pelagic Species Fishery and Recommended Acceptable Biological Catches Stock Assessment and Fishery Evaluation 2007.
- Schweigert, J. F., G. A. McFarlane, and Canadian Science Advisory Secretariat. 2002. Stock assessment and recommended harvest for pacific sardine in 2002. :12.
- Sumaila, U. R. 1995. Irreversible capital investment in a two-stage bimatrix fishery game model. *Marine Resource Economics* 10(3):263-83.
- Sumaila, U. R. 1999. A review of game theoretic models of fishing. *Marine Policy* 23(1):1-10.
- Washington Department of Fish and Wildlife. 2007. Summary report of the 2006 experimental purse seine fishery for pacific sardine (*sardinops sagax*).
- Wiedoff, B., and J. Smith. 2006. Oregon's Sardine fishery 2006 summary. Oregon Department of Fish and Wildlife, .