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Fishing Games Under Climate Variability: Transboundary Management of Pacific Sardine in the California Current System

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ABSTRACT

Pacific sardine (*Sardinops sagax*), which is a transboundary resource targeted by Mexican, U.S. and Canadian fisheries, has exhibited extreme decadal variability in its abundance and geographic distribution corresponding to water temperature regime shifts within the California Current Ecosystem. Our study develops a three-agent bioeconomic framework that incorporates environmental effects on sardine abundance and biomass distribution. Simulations are conducted to evaluate the conservation and economic benefits of various management strategies for the time variant/asymmetric shares of the Pacific sardine resource by three countries.

I. 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)[1]; 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 variability[2], 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 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.

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 stock[3] 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 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 late1990s.

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 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.

[Figure 1 HERE]

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)[4], 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 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.

[Figure 2 HERE]

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, 2007). The Pacific sardine fishery has three participating nations: Mexico, the U.S. and Canada. These countries may 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.

II. 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 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.

[Figure 3 HERE]

Sea surface temperature development model

We use a base trend of a SST (τ) described by Equation [1]5;

$$\tau_{y+1} = \tau_y + \mu + \sigma \Delta z_y \quad [1]$$

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

where *y* is year. Equation [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 μ=0.044 represents a 0.044^{o}C increase in temperature with one time step. This study evaluates two scenarios for SST trends; 1) an increasing (time-increment) SST trend (μ =0.044) which characterizes the warm regime; and 2) a decreasing (time-decrement) SST trend (μ = - 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.

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 ^{o}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 ^{o}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]. 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;

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

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

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

where *w* is country and *y* is year. In the simulations, we set the initial SST at 17.9^{o} 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 4).

[Figure 4 HERE]

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:

$$\hat{D}_{w,y} = \rho \cdot D_{w,y} + (1-\rho)\hat{D}_{w,y-1} \quad [3]$$

$$s.t. \quad 0 \le \hat{D}_{w,y} \le 1$$

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

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. For example, ρ = 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 ρ = 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.

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:

$$G(S) = -e\eta S \ln\left(\gamma \frac{S}{I}\right) \quad [4]$$

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 [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:

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

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

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

$$\widehat{h}_y^w = \widehat{D}_{w,y} \cdot B_y - S_{w,y} \qquad [7]$$

$$s.t.\ 0 \le \widehat{D}_{w,y} \le 1$$

$$\widehat{D}_{MX,y} + \widehat{D}_{US,y} + \widehat{D}_{CA,y} = 1$$

Due to time-variant biomass distribution and information delays regarding the biomass distribution, the target catch ($\widehat{h}$) 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:

$$h_y^w = \min\left\{D_{w,y} \cdot B_y, \widehat{h}_y^w\right\} \qquad [8]$$

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

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

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.

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 singletonnes 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.

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:

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

where d is the discount factor, and $G(S)$ is the surplus growth function in Equation [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 this constant economic benefits[7] 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 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, $0 \le S \le B$. 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 [9]:

$$S^*_{solo,y} = \frac{\tau_y}{\gamma} e^{-\left(1+\frac{1-d}{d e \eta}\right)} \qquad [10]$$

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:

$$\max \quad f_{w,y}(S^{*}_{w,y}) = p \cdot (\widehat{D}_{w,y} \cdot B_{y} - S^{*}_{w,y}) + \frac{\widehat{D}_{w,y} \cdot d \cdot p \cdot G(S^{*}_{w,y})}{1-d} \qquad [11]$$

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 ($S^{Minor*}_{w,y}$); 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:

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

Hanneson'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 singletonnes in Game IV and V.

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.

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:

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

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.

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:

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

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

$$PV_w^k = \sum_{y=1}^{35} d^{y-1} \cdot \pi_{w,y}^k$$
$$\pi_{w,y}^k = \dot{p} \cdot h_{w,y}^k \qquad [15]$$

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.

III. Results

SST, biomass distribution and carrying capacity

Table 1 shows the percentages of years that each country behaved as a major player based on the expected biomass distribution (see Equation [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.

[Table 1 HERE]

Net present value

Compared to the non-cooperative game, both cooperative games suggested positive externalities through cooperative transboundary management (Table 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), 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.

[Table 2 HERE]

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.

Conservation indicator

Significant conservation benefits were projected to result from cooperative transboundary management of the Pacific sardine resource (Table 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 3).

[Table 3 HERE]

The effects of the weighting factor on the information delay are explicit for the conservation indicators (Table 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. While in the two coalition cases (Game IV and V) higher ρ values result in relatively low conservation risk, the opposite, higher conservation risk, occurs in non-cooperative management. This risk in non-cooperative management is due to rapid stock depletion that occurs at the moment that the U.S. changes in position from major to minor country with higher discount rates (hence the lower optimal biomass maintained by the U.S. as a major country).

IV. 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 conversation 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 decisionmaking 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.

V. 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.

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Tables

Table 1 The percentage of time that each country is a major player and percentage of time all countries are minor players (for ρ=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 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 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	***0***	***0.25***	***0.5***	***0.75***	***1.00***
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	***0***	***0.25***	***0.5***	***0.75***	***1.00***
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 titles

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

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

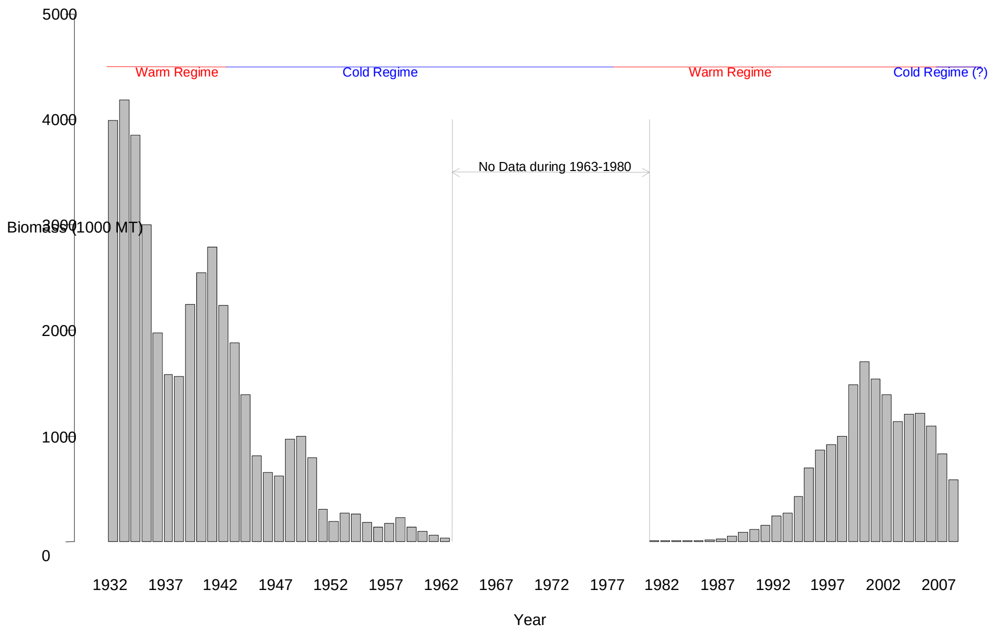

Figure 1

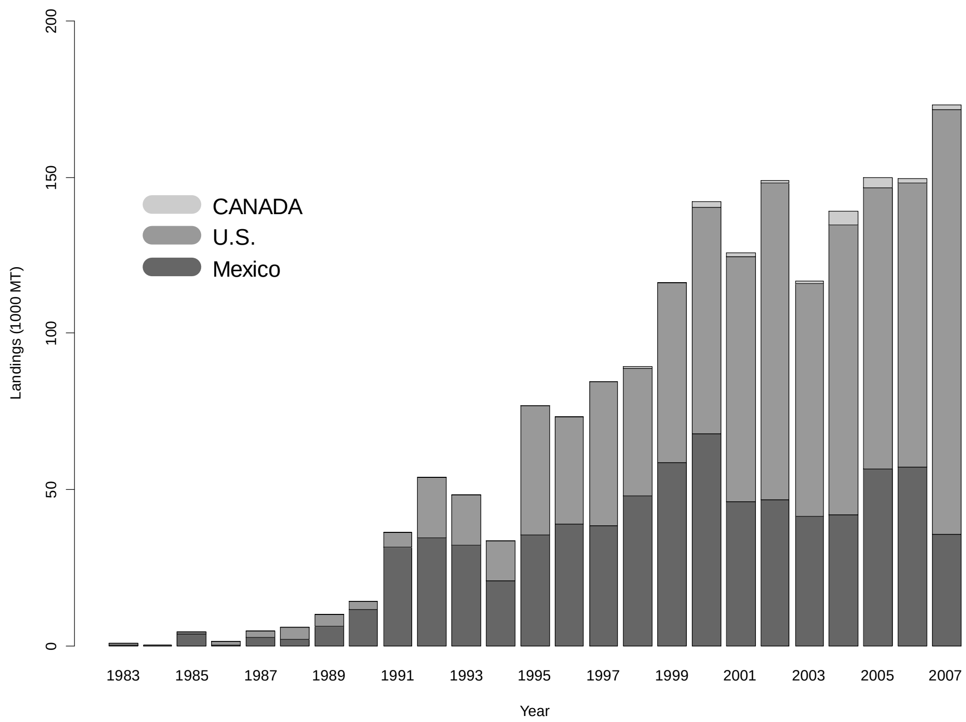

Figure 2

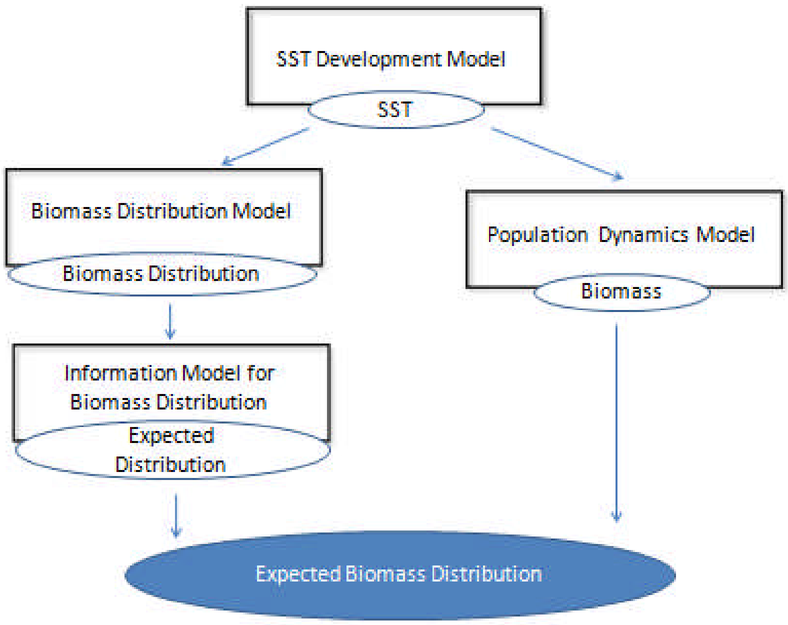

Figure 3

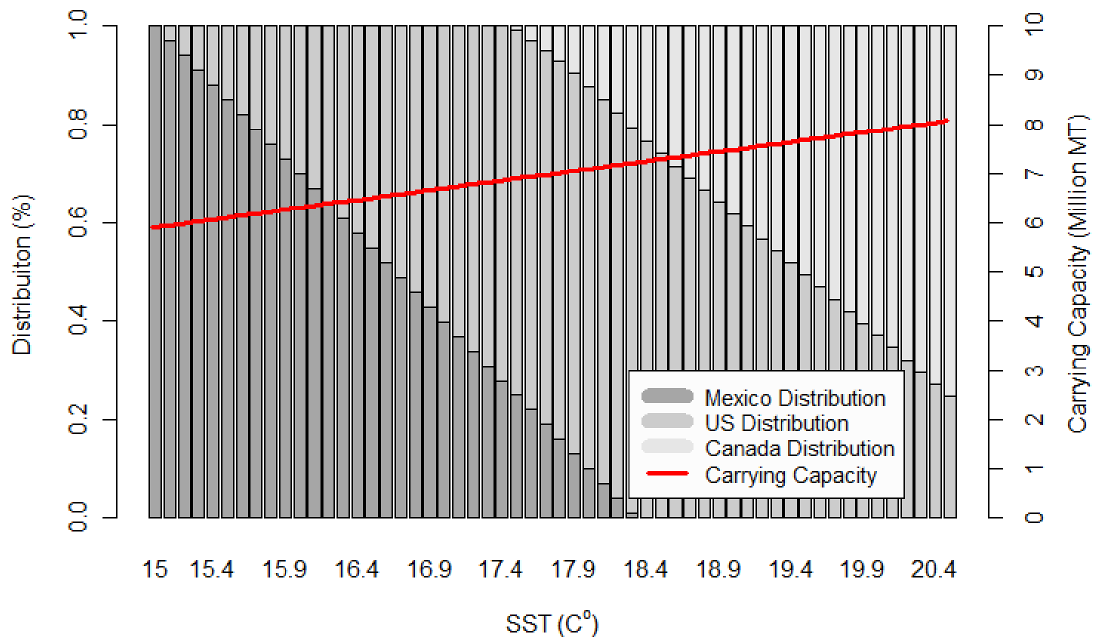

Figure 4

ENDNOTES

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

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

3 It is widely recognized and accepted that at least three substocks of Pacific sardine inhabit the CCE (Felix-Uraga *et al.*, 2005*a*; 2005*b*). 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.

4 SST at the Scripps Institute of Oceanography pier, in La Jolla, California, is used in their study.

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

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

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