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

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The case study of the Pacific sardine fishery in the California Current

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Abstract

The time variant/asymmetric distribution of a fish stock caused by climate variability is one of the challenges to the stability of cooperative management of a transboundary fish stock. Pacific sardine (*Sardinops sagax),* which *ex*hibit extreme decadal variability in abundance and geographic distribution corresponding to water temperature regime shifts within the California Current Ecosystem (CCE) is expected to face such issues. Pacific sardine is a transboundary resource which is caught by Mexican, U.S. and Canadian fisheries. Our study applied a three-agent bioeconomic framework that incorporates environmental effects on Pacific sardine abundance and biomass distribution. Simulations were conducted to evaluate the stability of full and partial cooperative management of Pacific sardine fisheries under six different climate variability scenarios. Our results show that ocean climate variability is an obstacle to the formation of stable full cooperative management outcomes for the Pacific sardine fisheries operated by Canada, the U.S. and Mexico.

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.

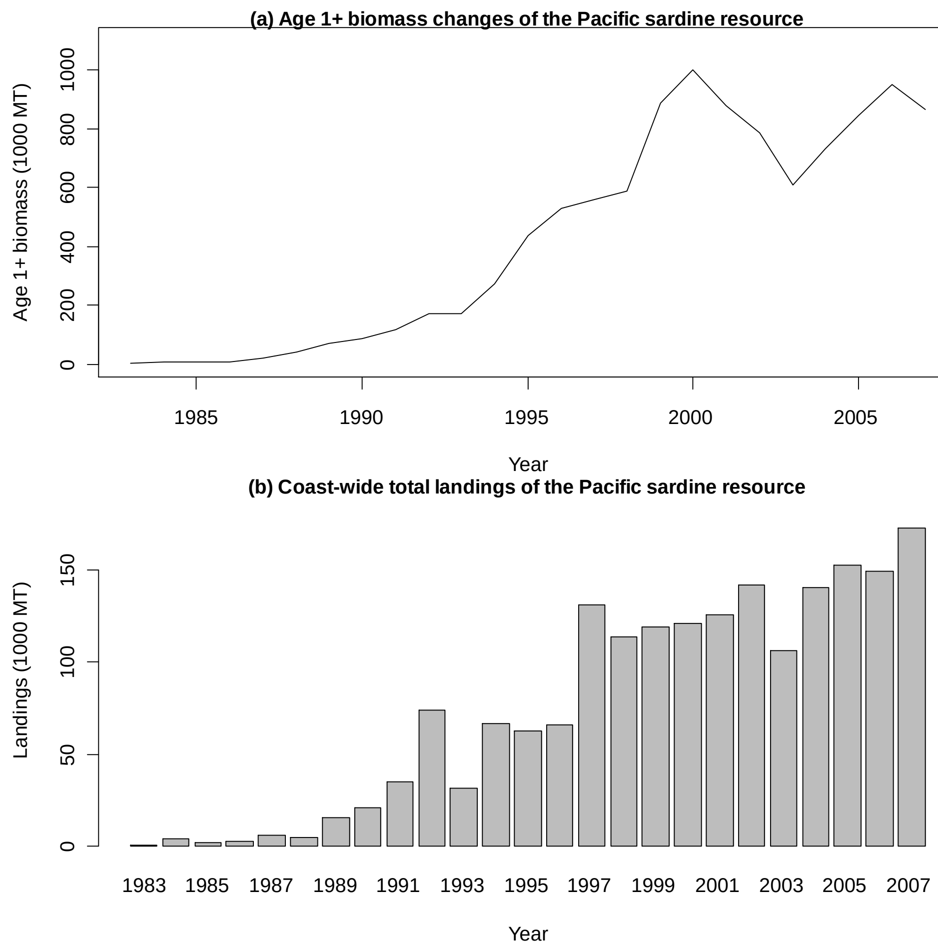
Material and methods

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 1a). Total coast-wide landings increased rapidly beginning in the early 1990s (Figure 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.*, 2009).

[Figure 1 HERE]

Figure 1:



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.

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. Therefore, 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 2004 a, 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; Aguero 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.

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.

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:

$$\tau_{y+1} = \tau_y + \mu + \sigma \Delta z_y \tag{1}$$

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

where y is time. Equation (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 μby two and three for both time–increment and decrement trends. Scenarios in this paper are then, 1) time-increment SST trend (μ= 0.044); 2) time-increment SST trend (μ= 0.088); 3) time-increment SST trend (μ= 0.132); 4) time-decrement SST trend (μ= - 0.044); 5) time-decrement SST trend (μ= - 0.088) and 6) time-decrement SST trend (μ= - 0.132). We begin with an initial SST of 17.9 ^{o}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.

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 (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:

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

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

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

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.

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:

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

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

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

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

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. 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).

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:

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

$$h_y = B_y - S_y$$

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.

Economic outcomes-present value

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

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

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 (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 reasonable[1]. As an approximate of net economic benefit, we therefore apply a constant net price for catch of 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:

$$j_w = \sum_{y=1}^{35} \pi_{w,y}^{k} \cdot d^{y-1} \qquad (6)$$

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

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.

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

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).

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).

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

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.

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):

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

where $G(S)$ is the growth term in the surplus function, the second term in the right hand side in Equation (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 (9):

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

(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 ($\hat{D}_{\min or} < 0.5$) 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:

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

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

$$\widehat{h}_{w,y} = \widehat{D}_{w,y} \cdot B_y - S^*_{w,y} \tag{13}$$

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

$$h_{w,y} = \min\left\{D_{w,y} \cdot B_y, \widehat{h}_{w,y}\right\} \tag{14}$$

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) {Canada, U.S., Mexico}$_d$; 2) {Canada, U.S., Mexico}$_f$; 3){Canada, US}; 4) {U.S., Mexico}; 5) {Canada}; 6) {U.S.}

and 7) {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 realize 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 singletonnes (e.g., Lindroos and Kaitala 2000). Coalitions 3 and 4 are two-country coalitions with free-rider singletonnes. Note that a coalition of Mexico and Canada would not be feasible due to their geographical separation. This study, therefore, studies only two two-coutry coalitions, namely {Canada, US} and {U.S., Mexico}. Coalitions 5, 6 and 7 are so called singletonnes, 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:

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

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

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

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

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

These values are calculated and presented in the next section.

Results

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 ^{o}C, 3.1 ^{o}C and 4.7 ^{o}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 ^{o}C, 3.1 ^{o}C and 4.7 ^{o}C by the end of the 35-year period. At the initial setting of 17.9 ^{o}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 ^{o}C, the major player position shifted to Canada. As the SST decreased over time and the SST fell below 16.7 ^{o}C, the major player position shifted to Mexico; between 16.7 ^{o}C and 19.4 ^{o}C, the U.S. held the major player position.

Economic outcomes

All payoff results derived from the simulations are summarized in Table 1. For all scenarios, grand coalitions with dynamic transferable catch shares ({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 (singletonnes) 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.

[Table 1 HERE]

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 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 singletonnes 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 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 μ= -0088 and 294 million USD forμ= - 0.132 which exceeded the sum of payoffs from singletonnes, 234 million USD and 253 million USD respectively. For time-decrement SST scenarios, where μ= - 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 whereμ= - 0.044 consisted of singletonnes, engaged in non-cooperative management.

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 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).

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 μ= -0.088 or - 0.132 was stand-alone stable. In the time-decrement SST scenarios where μ= - 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 μ= - 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 μ= 0.044 (Table 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 μ= - 0.088 or μ= - 0.132 (Table 1 b-2 and 3). In the time-decrement SST scenarios for μ= - 0.044 or μ= - 0.088, 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 μ= - 0.044 (Table 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, only one of the decreasing SST scenarios (μ= - 0.132 in Table 1 b-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 Bradt 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 (μ= - 0.88 and μ= - 0.132), and was favorable in terms of reducing the risk of overexploitation of the sardine stock relative to non-cooperative management. Besides singletonnes, there is no stand-alone coalition for time-decrement SST scenarios for μ= - 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.

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.

References

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

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

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

Bakun, A. 1998. Ocean triads and radical interdecadal variation: Bane and boon to scientific fisheries management. Kluwer Academic, Dordrecht.

Brander, K.M. 2007. Global fish production and climate change. Proc. Natl. Acad. Sci. 104(50): 19709-19714.

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

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

Fox, W. W. 1970. An exponential yield model for optimizing exploited fish populations. Trans. Am. Fish. Soc. 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* Climate change and the economic of the world's fisheries. *Edited by* Hannesson, R., Barange, M and Herrick, S. Edward Elgar Publishing, Northampton.

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

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

Ishimura, G., Sumaila, U.R., and Herrick, S. 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 MacCall, A.D. 1995. Stock-recruitment models for pacific sardine (Sardinops sagax). Can. J. Fish. Aquat. Sci. 52(3): 566-577.

Jacobson, L.D., Bograd, S.J., Parrish, R.H., Mendelssohn, R., and Schwing, F.B. 2005. An ecosystem-based hypothesis for climatic effects on surplus production in California sardine (Sardinops sagax) and environmentally dependent surplus production models. Can. J. Fish. Aquat. Sci. 62(8): 1782-1796.

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

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

Kronbak, L. G., and Lindroos, M. 2007. Sharing rules and stability in coalition games with externalities. Mar. Resour. Econ. 22(2):137-154.

Laukkanen, M. 2003. Cooperative and non-cooperative harvesting in a stochastic sequential fishery. J. Environ. Econ. Manage.45(2): 454-473.

Li, E. 1998. Cooperative high-seas straddling stock agreement as a characteristic function game. Mar. Resour. Econ. 13(4):247-58.

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

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

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

McKelvey, R., Golubtsov, P., Miller, K. and Crip, G. 2006. Bi-national management of a transboundary marine fishery: modelling the destabilizing impacts of erratic climate shifts. *In* Climate change and the economic of the world's fisheries. *Edited by* Hannesson, R., Barange, M and Herrick, S. Edward Elgar Publishing, Northampton.

MacCall, A. D. 1976. Density dependence of catchability coefficient in the California Pacific sardine, Sardinops sagax caerulea, purse seine fishery. Rep. CCOFI. 18:

136-148.

MacCall, A. D. 1990. Dynamic geography of marine fish populations. University of wavb Washington Press, Seattle USA.

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

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

Munro, G.R. 1979. The optimal management of transboundary renewable resources. Can. J. Econ. 12(3):355-76.

Munro, G.R. 1990. The optimal management of transboundary fisheries: Game theoretic considerations. Natural Res. 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., Houtte, A., and Willmann, R. 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., Low, P.J., Ellis, J.R., and Reynolds, J.D. 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 Res. 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. 1981. The collapse of the California sardine fishery: what have we learned? *In* Resource Management and Environmental Uncertainty. *Edited by* M. H. Glantz and J. D. Thompson, New York, US: John Wiley & Sons.

Rodriguez-Sanchez, R., D. Lluch-Belda, Villalobos, H., and Ortega-Garcia, S. 2002. Dynamic geography of small pelagic fish populations in the California current ecosystem on the regime time scale. Can. J. Fish. Aquat. Sci. 59(12):1980-1988.

Sumaila, U. R. 1995. Irreversible capital investment in a two-stage bimatrix fishery game model. Mar. Resour. Econ. 10(3):263-83.

Sumaila, U. R. 1999. A review of game theoretic models of fishing. Mar. 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. Rep. CCOFI.33:76-86.

Yi, S. 1997. Stable coalition structures with externalities. Games Econ. Behav. 20(2): 201-237.

Tables

Table1: 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 (μ=+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 (μ=+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 (μ=+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 (μ=-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 (μ=-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 (μ=-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 caption

Figure 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).