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Increasing the economic value of the eastern Pacific Ocean tropical tuna fishery: Tradeoffs between longline and purse-seine fishing

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ABSTRACT

Fisheries harvesting yellowfin and bigeye tuna while targeting skipjack in the Eastern Pacific Ocean (EPO) are not managed optimally with respect to economic value. Bigeye tuna are generally caught at before they reach full size so cannot fetch the higher prices obtained for mature fish which are usually harvested by longline fleets and sold to the sashimi market. This study evaluates the economic and biological trade-offs of managing the fishery to determine how the economic value may increase with different harvest strategies while the spawning biomass of both species is maintained at the optimal sustainable levels. This study uses three analytical models to assess the economic and biological tradeoffs in four possible scenarios with different combinations of purse-seine and longline fishing effort. The first model evaluates the biological tradeoffs under various effort combinations of longline (LL) and purse-seine (PS) that could reach the same optimal biomass level, measured by the spawning biomass ratio (SBR). The second model evaluates the long-term optimal equilibrium economic value under various effort combinations. The third model evaluates the dynamic (short-term) trajectory of recovery path of bigeye tuna under various policy options. The analytical results show that economics and conservation are not incompatible. In one scenario, we show that reducing purse-seine effort by 26.3%, via a per-ton compensation system from longline fleets to the purse-seine, leads to net economic gain of $93 million, annually. The total value of the PS and LL fisheries in EPO increases from $1246 million to $1339 million. The study shows that the economic value of the resource is highly dependent on the allocation of effort between the longline and purse-seine fisheries. Since the longline and purse-seine fisheries in EPO are formed by multiple users in multiple countries/groups, the ideal scenarios would not be feasible without administrative measures and/or economic incentives. This study also discusses three possible ways of implementing a management strategy that would achieve higher economic value while still maintaining tuna conservation goals, such as a tradeable right-based management scheme.

1. Introduction

Sustainable management measures and a fair allocation scheme to all participants for fishing opportunities amongst fishing nations are two key issues in exploiting the resources of highly migratory tuna species. The stock status of each tuna species is reviewed formally by each of the tuna Regional Fisheries Management Organizations (RFMOs) based on two aspects: whether the biomass (or spawning biomass) is above or below the biomass-based reference point; and whether fishing mortality is higher or lower than the fishing mortality-based reference point, which are often set to those corresponding to maximum sustainable yield (MSY) (Miyake et al., 2010; Guillotreau et al., 2017). Despite different approaches and practices, the tuna RFMOs had mixed success at limiting fishing effort (Joseph et al., 2010). Based on the most recent status of stocks reported by RFMOs (IATTC, 2018), the current fishing mortality of both the yellowfin and bigeye tuna in the EPO are slightly below the fishing mortality that produces maximum sustainable yield (MSY). However, these interpretations are uncertain and highly sensitive to the assumptions made about the steepness parameter (h) of the stock-recruitment relationship, the average size of the oldest fish (L2), and the assumed levels of natural mortality (M). Results are more pessimistic for stocks for which

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there are not adequate management measures to end overfishing (ISSF, 2018).

Moreover, it appears that misalignment of economic incentives with conservation objectives and the allocation conflicts among countries with different fishing gears hampered the overall conservation efforts of the RFMOs. If individual countries lack adequate rights to a portion of the quota, they have a perverse motivation to "race to fish". This race can lead to poor stewardship and lobbying for ever-larger harvest quotas, creating a spiral of reduced stocks, excessive harvests, and eventual collapse. Rights-based management could permit quota trading from one party to another in an efficient and equitable distribution of the benefits. This can only be successful if there are transparent methods to measure biological and economic tradeoff and sustainably.

The fishery for tropical tunas in the EPO focuses on three species; yellowfin tuna, *Thunnus albacares*, bigeye tuna, *T. obesus*, and skipjack tuna, *Katsuwonus pelamis*. Yellowfin and bigeye are not managed optimally with respect to either catch or the economic value of the catch. Both species are generally caught at sizes too small to take full advantage of the growth of the individual fish or of the higher prices obtained for larger fish in the sashimi market.

Most of the catches are taken by two types of gear, purse-seine and longline. Smaller bigeye, yellowfin, and skipjack destined for the canned tuna market are caught in the purse-seine fisheries, while large bigeye and yellowfin destined for the sashimi market are caught in the longline fishery. In EPO, purse seine caught 95% of the yellowfin, 61% of the bigeye, and 80% of the skipjack (ISSF, 2018). As purse seine fishing gear selects smaller tuna than longline gear, this form of growth overfishing can reduce tropical tuna fishery productivity through a loss of yield per recruit. Optimizing catches and revenue, therefore, requires an understanding of both economic and biological processes to evaluate the tradeoffs among different management actions (Campbell and Nicholl, 1995; Bertignac et al., 2000; Sun et al., 2017).

Purse-seiners make three types of sets; sets on tunas associated with dolphins, sets on tunas associated with floating objects (natural or by purse-seiner fishing vessels), and sets on tunas in unassociated schools. In general, sets on tunas associated with dolphins catch large yellowfin, and sets on floating objects and on unassociated schools catch skipjack and small bigeye and yellowfin. Longline vessels catch large yellowfin and large bigeye.

There are two types of floating objects, flotsam and fish-aggregating devices (FADs). The use of FADs has increased since 1994 and reaches 97% of all floating-object sets by vessels with > 363 t carrying capacity in recent years (IATTC, 2018). The purse-seine fishery on tunas associated with FADs expanded rapidly starting in the early 1990s, and this has had a substantial impact on the catches of skipjack and bigeye tuna, since most of the 2016 skipjack catch was taken in sets associated with FADs, and bigeye catches were taken in sets on FADs between 5°N and 5°S.

The assessment of tropical tunas in the EPO is conducted by the Inter-American Tropical Tuna Commission (IATTC), and their most recent stock assessment reports confirm that the longline fishery had the greatest impact on the stock prior to 1995. With the decrease in longline effort and the expansion of the floating-object fishery, at present the impact of the purse-seine fishery on the bigeye stock is far greater than that of the longline fishery (IATTC, 2018). It has been shown that growth overfishing occurs for both bigeye and yellowfin tuna, but it is uncertain whether recruitment overfishing of either species is occurring. The expansion of the purse-seine fishery on floating objects in the early 1990s has caused growth overfishing of bigeye tuna due to high exploitation rates and the small size of fish selected by the fishery.

IATTC has the authority to manage both bigeye and yellowfin tuna stocks at levels that will support maximum sustainable yield (MSY). The IATTC sets seasonal closures for purse seiners and catch limits for the member countries with longliner fleets. Empirical work in this paper is based on IATTC 2008 assessment results, which was determined using a Stock Synthesis (SS) assessment model. Under the allocation of effort in 2008 (IATTC, 2010), MSY for bigeye occurs at a spawning biomass level (SPR) that is 19% of the unexploited level, while the 2008 stock assessment showed that SPR was as low as 12%. IATTC resolution recommended reducing both the longline and purse-seine fishing effort proportionally by 20.5% during 2009–2011 (IATTC, 2009).

Given the different sizes and landed values of tuna caught by the two fishing gears, it is unlikely that this recommended approach would achieve optimal catches in either weight (MSY) or economic value (MEY). It appears that the fishery could benefit from curtailing purse-seine fishing on bigeye tunas. However, the two fishing methods are conducted by vessels from different nations and catch different species compositions, so social and equity issues need to be addressed. This study first analyzes the trade-offs and demonstrates alterative harvest strategies with optimal improved economic value. It then discusses the possible management tools that may address social and equity issues between the two gears.

We use three hypothesis modelling analyses to evaluate the economic and biological tradeoffs of different levels of purse-seine and longline fishing effort on the equilibrium catch, spawning biomass, and economic value of tropical tunas in EPO. The first hypothesis is to specify a model to evaluate the biological tradeoffs under various effort combinations of longline and purse-seine that could reach the same optimal biomass level, measured by the spawning biomass ratio (SBR). The second hypothesis model evaluates the long-term optimal equilibrium economic value under various effort combinations. The third hypothesis model evaluates the dynamic (short-term) trajectory of recovery path of bigeye tuna under various policy options.

2. Methods

Sun et al. (2017) demonstrated that RFMOs can coordinate multilaterally to facilitate an increase in market prices in order to change economic incentives and reduce fishing pressure on skipjack and yellowfin tuna. Managers could also employ predictive tools, such as sequential random utility models developed in Sun et al. (2016), which were applied to purse-seine vessels in the EPO to predict the distribution of fishing effort over space and time to anticipate future changes in climate, fuel costs, and stock abundance (Green and Broadhead, 1965; Sun et al., 2016). Additionally, rights-based management could permit quota trading from one party to another in an efficient and equitable distribution of the benefits, under transparent methods to measure biological and economic tradeoffs (Sun et al., 2019). Therefore, the objective of this study is to estimate tradeoffs of economic value of the fisheries between purse-seine and longline fishing effort.

The definition of overfishing with respect to either catch in weight of fish or economic value is more complicated than the simplistic reference points commonly used for fisheries management. A stock is overfished if fishing has reduced its abundance to the extent that it cannot produce the MSY or MEY.

Production of MSY will be analyzed first. Whether overfishing (or underfishing) occurs depends on the size of fish caught and the amount of effort that is deployed. There are two types of overfishing, "growth overfishing[1]" and "recruitment overfishing." Growth overfishing could occur when the fishing gear catches fish that are too small or when the

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[1] The biomass of a cohort of fish (a group of fish hatched at about the same time) increases when the fish are relatively young because weight gains due to growth exceed the losses in weight to it due to natural mortality. Eventually, as the fish age, the gains due to growth and the losses due to natural mortality are equal, at which point the fish are said to have reached the "critical size." After that the gains due to growth are exceeded by the losses due to natural mortality, and the biomass decreases. If substantial amounts of smaller, younger fish are caught, growth overfishing occurs because greater catches could be realized if the biomass were permitted to increase.

fishing mortality is high using an unselected gear that catches a wide range of sizes of fish, including a large amount of juvenile fish. Recruitment overfishing occurs when the abundance of mature fish is reduced by fishing to the point where recruitment of young fish is reduced.

We continue with the goal of MSY in weight of fish catch. If more than one type of gear is employed in a fishery, different sizes of fish will be caught by each. The total weight of fish caught can be maximized by maximizing use of the type of gear that catches fish that are close to the critical size and minimizing use of the type of gear that catches younger, smaller fish. At the same time, the managers of the fishery must ensure that the fishing mortality stays below the threshold which would result in either growth or recruitment overfishing.

We turn now to the goal of maximum sustainable economic yield (MEY) in value of fish catch. In this scenario, the “critical value,” rather than the critical size, is of interest. The goal is to maximize use of the type of gear that catches the most valuable fish and to minimize use of the type of gear that catches the least valuable fish. The value of a fish is not necessarily proportional to its weight; therefore, a management scheme that evaluates the weight of the catch based on a biological model would not necessarily maximize its value based on an economic model, as discussed in the following section.

2.1. Stock assessment and biological tradeoffs

The analyses are based on the IATTC's stock assessments for bigeye and yellowfin tuna and the recent average catch levels for skipjack tuna to evaluate the effect of various effort reduction programs of purse-seine and longline effort (Aires-da-Silva and Maunder, 2010; Maunder and Aires-da-Silva, 2010; Maunder, 2010). The stock assessments for bigeye and yellowfin species are carried out using Stock Synthesis II (Methot, 2005), which is age-structured and takes into account the different sizes of tuna caught by the different fishing methods and set types. No reliable stock assessment is available for skipjack tuna, although in general, the stock of skipjack is healthy. Therefore, changes in equilibrium catches for skipjack were assumed to be proportional to changes in purse-seine equilibrium catches for yellowfin tuna. (The average annual skipjack catch for 2001–2007 was multiplied by the ratio of the equilibrium yellowfin purse-seine catch to the equilibrium yellowfin purse-seine catch under the effort allocation in 2008.)

It is assumed that if the catches of small bigeye and yellowfin were reduced, the gains to the biomass of those species due to growth would exceed the losses due to natural mortality. Thus, this would increase the availability of large bigeye and yellowfin to the longline fishery which, in turn, would increase the total catches and value of those species. It is also assumed that bigeye and yellowfin are well mixed within the EPO; therefore, reductions in catching small tunas anywhere in the EPO would be beneficial to longliners operating anywhere in the EPO. It is further assumed that the purse-seine and longline fisheries could be managed so that the spawning biomasses of the two species are maintained at optimum levels.

Few bigeye tuna are caught by the purse-seine sets on tuna associated with dolphins. Although about 98% of bigeye caught by purse seiners are fished by floating objects, the steady-state equilibrium results presented in this study are based on treatment of all purse-seine effort proportionally. This is partly due to the difficulties in restricting purse-seine vessels on different set types since vessels that fish on dolphin associated tuna can also set on floating objects and unassociated schools. Encouraging fishermen to make sets on tunas associated with dolphins might increase the purse-seine catches of yellowfin, since most of the yellowfin caught in such sets are close to the critical size. However, the economic value of a purse seine caught yellowfin is lower than a longline caught yellowfin. In all scenarios, the characteristics of the different purse-seine set types are maintained separately, but the effort changes are assumed proportionally across each set type.

Table 1
Frozen bigeye, yellowfin, and skipjack prices in 2007 and 2008.

Market Year and Species	Ex-vessel prices[a] in Mexico and Ecuador ($/mt)		Auction prices[b] in Tsukiji, Tokyo, Japan ($/mt)	
	2007	2008	2007	2008
Yellowfin	$1710	$1945	$7858	$9579
Bigeye	$1568	$1783	$9576	$12,271
Skipjack	$1425	$1621		–

[a] Personal communication from the tuna processors in Mexico and Ecuador for landings caught by tuna purse seine fishery.
[b] Personal communication from the auction market in Tsukiji, Tokyo, Japan for landings caught by tuna longline fishery.

2.2. Definition of fishery's economic tradeoffs

The economic value was calculated by summing ex-vessel prices multiplied by total landings for each of the three species and each gear type. In the dynamic calculations, the value is summed over all projected years. Note that the total ex-vessel economic value is lower than the possible value-added final product value for various types of consumption after processing.

It is also notable that the auction prices for sashimi-grade frozen bigeye and yellowfin tuna caught by longline for the Japanese market are about 4–6 times higher than the ex-vessel prices observed for cannery grade tuna caught by purse-seiners. Price information for 2007 and 2008 for both gear types is shown in Table 1 (Sun and Chiang, 2010).

Prices from 2007 are used to calculate the steady-state equilibrium landings values to match the stock assessment model, which is based on data ending in 2007. Prices from 2008 are used to calculate the dynamic projection over the period 2008–2018.

2.3. Condition of the spawning biomass of bigeye tuna recover to the target level

The stock assessment model for bigeye and yellowfin tuna is used to generate the spawning biomass ratio (SBR; the ratio of the current spawning biomass, S, to the spawning biomass of the unexploited stock, S_0), catch, and maximum economic value of the fisheries for different levels of longline and purse-seine fishing effort in a steady state (Christensen, 2010). All possible effort combinations are specified to investigate the tradeoffs under the condition that the spawning biomass of bigeye tuna recover to the target level.

Based on Aires-da-Silva and Maunder's (2010) estimation from their stock assessment model, the SBR corresponding to the MSY of bigeye is about 0.19, i.e. the spawning biomass at 19% of the unexploited level in a steady state. Therefore, the management goal should be avoiding a decrease in SBR to less than 0.19. We evaluate the catch and economic value of the fisheries under the following scenarios: (A) effort allocation between the two gears in 2008; (B) equal proportional reduction in effort for longline and purse-seine effort that would support MSY for bigeye tuna (SBR = 0.19), (C) fixed longline effort and a reduction in purse-seine effort so that SBR = 0.19; and (D) fixed purse-seine effort and a reduction in longline effort so that SBR = 0.19.

Through the IATTC's Stock Synthesis II assessment model to estimate the SBR, the dynamic projections generate catch and economic value of the fisheries over the period of 2008–2018, for different levels of longline and purse-seine fishing efforts under the conditions defined above.

3. Results

This study uses three analytical models to evaluate the economic and biological tradeoffs at four possible scenarios with different

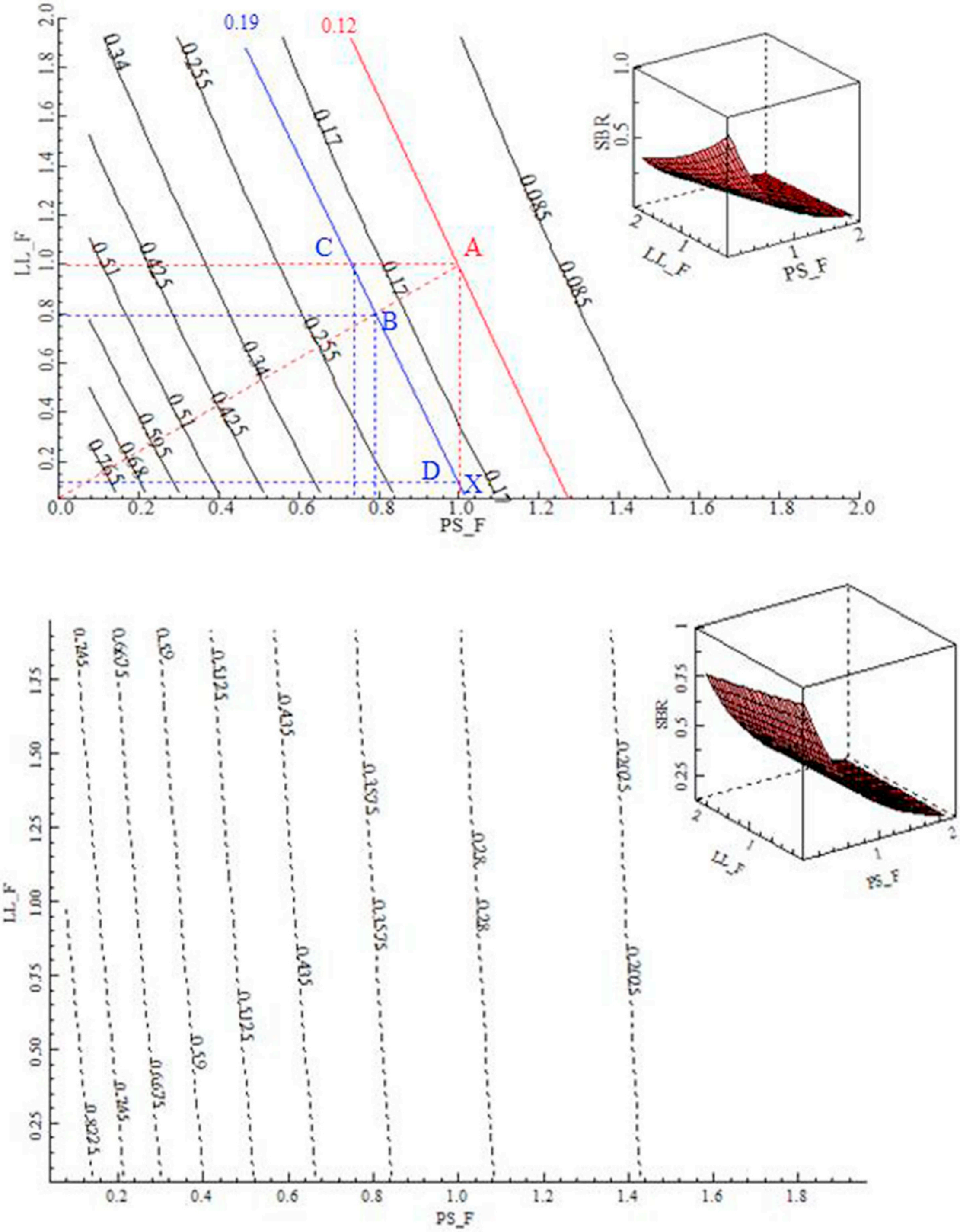

Fig. 1. Surface and contour plots of equilibrium bigeye tuna (upper panel) and yellowfin tuna (lower panel) spawning biomass ratio (SBR) under different purse-seine (PS_F) and longline effort (LL_F) levels relative to effort levels in 2008.

combinations of purse-seine and longline fishing effort.

3.1. Biological tradeoffs in the long run steady-state

The first model evaluates biological tradeoffs under various effort combinations of longline and purse-seine that could reach the same optimal biomass level, measured by the spawning biomass ratio (SBR). The SBR, catch, and revenue are all sensitive to the purse-seine and longline effort in the long run, because all coefficients in this study are significantly different from zero. Bigeye and yellowfin SBRs appear to be linear functions of purse-seine and longline effort and, as expected, SBRs for both species increase when purse-seine and longline effort are reduced (Fig. 1), and catches for both species are reduced.

$$SBR_{BET} = 0.9078 - 0.5940{*}PS\_Effort - 0.2666{*}LL\_Effort;\ Adj - R^2 = 0.8908 \tag{1}$$

$$SBR_{YFT} = 0.9314 - 0.5283{*}PS\_Effort - 0.0764{*}LL\_Effort;\ Adj - R^2 = 0.9045 \tag{2}$$

The relationships between effort and catch are generated by

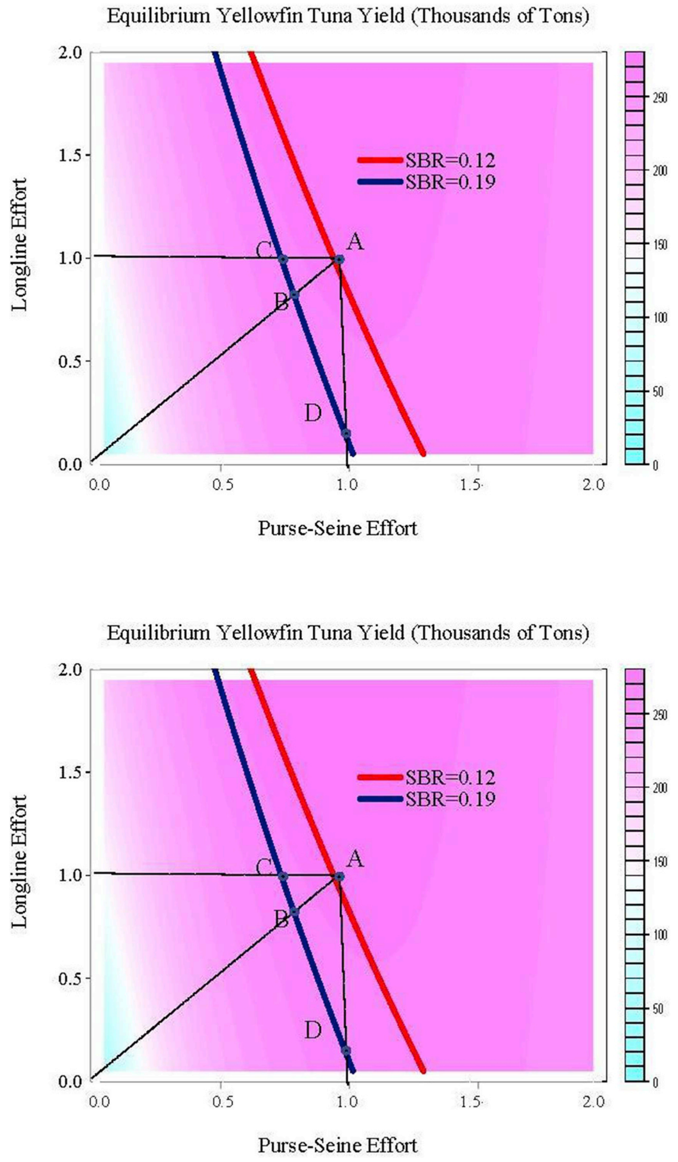

Fig. 2. Contour plots of bigeye tuna (upper panel) and yellowfin tuna (lower panel) steady-state catch under different purse-seine and longline effort levels relative to effort levels in 2008.

simulations while adjusting the effort of longline and the purse-seine fleets proportionally. Using the simulation model of a grid searching step of 0.01 on both PS and LL combinations to find the path to reach various levels of SBR, a total of 455 observations with different effort combinations of standardized longline and purse-seine ranging from 0 to 2 were found with SBR ranging from 0.18 to 0.20. These observations were used to estimate the tradeoffs in the analytical equation 3a through 7.

The relationship between effort and catch appears to be nonlinear (Fig. 2). The bigeye catches will increase dramatically as the purse-seine effort is reduced. However, it seems that the purse-seine effort is at the optimal level (MSY) for yellowfin; therefore, either an increase or a decrease in PS effort, particularly the latter, reduces the PS yellowfin catch. Holding the SBR at a constant level, total economic value increases as purse-seine effort is reduced and longline effort is increased (the longline efforts and purse-seine efforts form a negative slope, showing in Fig. 3). More yellowfin and bigeye would be available for longline fleets due to the reduction in purse-seine effort. leading to an increase in value of both yellowfin and bigeye (Fig. 3). The contour

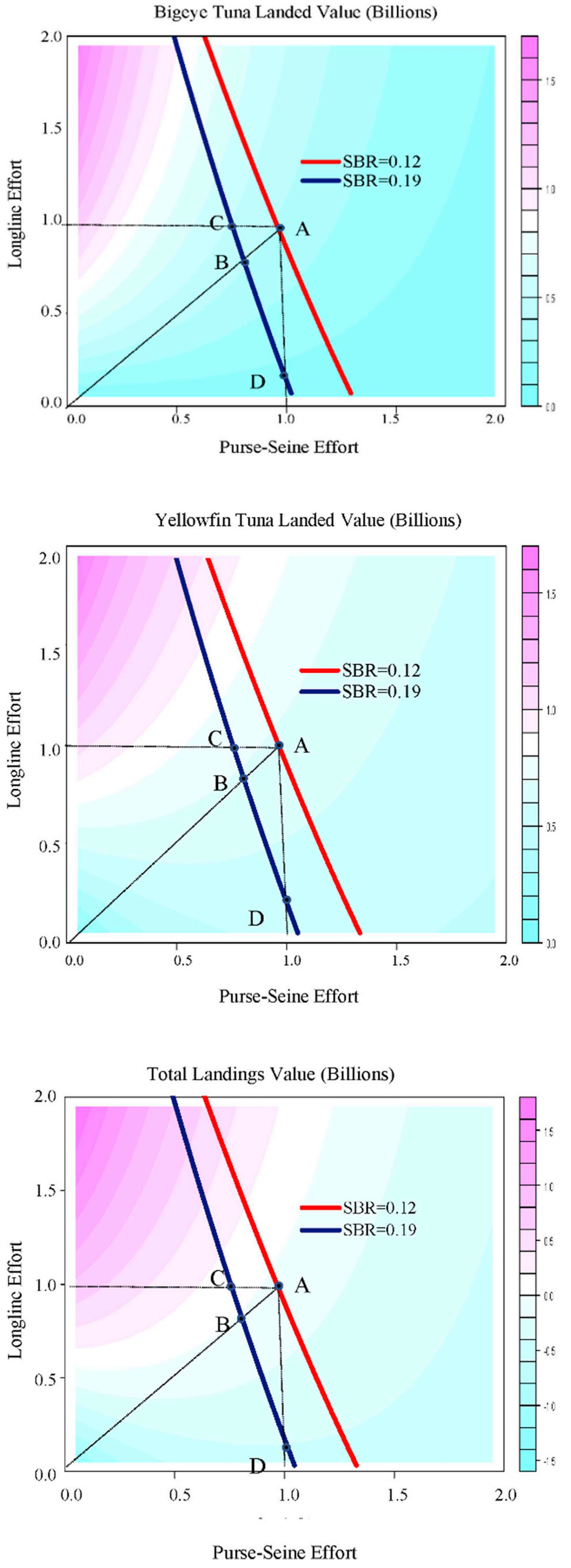

Fig. 3. Equilibrium revenue for bigeye tuna (upper panel) and yellowfin tuna (middle panel) and total landings values (lower panel) after adjustment for compensating the purse-seine fishery for lost catch under different purse-seine and longline effort levels relative to effort levels in 2008.

plots can be used to evaluate a range of effort allocation schemes. For example, if the longline effort is fixed at the level of 2008, the economic yield would be increased by reducing the purse-seine effort.

Since changes in skipjack catch are assumed to be proportional to changes in yellowfin catch, skipjack catch decreases with a decrease in purse-seine effort. However, since skipjack is not targeted by the longline fishery, skipjack catches change with changes in purse-seine effort only.

There are an infinite number of possible purse-seine and longline effort combinations that can produce a bigeye SBR of 0.19. The linear relationship, applying equation (3a), represents 99.75% goodness of fit in Adj-R^2, and the tradeoff can be understood as a 1% change of purse-seine effort corresponds to a 3.68% change in longline effort (as Equation (3a) shows).

$$LL\_EFFORT_{BET} = 3.77 - 3.68*PS\_EFFORT_{BET};\ Adj - R^2 = 0.9975 \quad (3a)$$

The tradeoff can also be evaluated in terms of catch with respect to standardized purse-seine effort.

$$PS\_CATCH_{BET} = 32{,}100 + 30{,}060*PS\_EFFORT_{BET};\ Adj - R^2 = 0.9654 \quad (3b)$$

$$LL\_CATCH_{BET} = 121{,}210 - 117{,}040*PS\_EFFORT_{BET};\ Adj - R^2 = 0.9771 \quad (3c)$$

where PS_CATCH_{BET} and LL_CATCH_{BET} are defined as bigeye tuna catches harvested by the purse-seine and by longline fishery, in metric tons, respectively. Such as shown in equations 3b and 3c, a 1% reduction in purse-seine effort would reduce the bigeye tuna catch by 301 tons and allow a 1170-ton increase in the longline catch.

In terms of catch between the two fisheries, the tradeoff, while maintaining the SBR at 0.19, manifests as a 1-ton reduction in purse-seine catch allowing a 3.85-ton increase in longline catch (see Equation (4)). The slope of the relationship is similar for other levels of SBR.

$$LL\_CATCH_{BET} = 243.63 - 3.85*PS\_CATCH_{BET};\ Adj - R^2 = 0.9894 \quad (4)$$

3.2. *Economic tradeoffs in the long run steady-state*

The second model evaluates the tradeoffs in the long-term equilibrium economic value under various effort combinations. Economic value can be substantially increased, while maintaining the equilibrium SBR at 0.19, by adjusting the effort of longline and the purse-seine fleets non-proportionally. Equations (5)–(7) illustrate the equilibrium relationships between revenue of longline fleet. LL_REV_{BET} and $Total\_REV_{BET}$ are defined as revenue generated by longline catches and by both longline and purse-seine catches, in millions of dollars, respectively.

Equation (5) shows that one ton of bigeye tuna not caught in the purse-seine fishery (valued $1540) would contribute $36,880 in revenue (= (-$36.88 million/thousand ton) * (−1 ton)) to the longline fishery. We may use that $1540 as compensation to the purse seine fishery for the forgone revenue. Therefore, equation (6) shows the net increase of total bigeye value from transferring bigeye quota between purse-seine and longline gears would be $35,340 per ton.

$$LL\_REV_{BET} = 2{,}332.97 - 36.88*PS\_CATCH_{BET};\ Adj - R^2 = 0.9894 \quad (5)$$

$$Total\_REV_{BET} = 2{,}333.71 - 35.34*PS\_CATCH_{BET};\ Adj - R2 = 0.9894 \quad (6)$$

As indicated in equation (7), a 1% reduction in purse-seine fishing effort would increase total revenue of PS and LL by $10.74 million (= $1074.45 million*1%) after considering the gain to the LL's revenue and the loss of PS's revenue due to the loss of skipjack catches by the purse seiners. In summary, this implies that a 1% reduction of PS standardized effort would reduce 300.6 tons in the catch of juvenile bigeye, based on equation (3b), and would still increase the total value of total catch by $10.74 million.

$$Total\_REV_{BET} = 1{,}211.03 - 1{,}074.45*PS\_EFFORT_{BET};\ Adj - R^2 = 0.9772 \quad (7)$$

Using the equations generated from the stock assessment models, the study developed five harvest strategies to evaluate the tradeoffs of the PS and LL and net gain of the entire fisheries. The five harvest strategies include 1) Scenario A: no change in fishing effort for both PS and LL (PS = 1, LL = 1), 2) Scenario B: 20.5% reduction for both PS and LL fishing effort (PS = 0.795, LL = 0.795), 3) Scenario C: 26.7% reduction for PS but no change in LL fishing effort (PS = 0.737, LL = 1), 4) Scenario D: 0% change in PS effort but 86.7% reduction in LL fishing effort reduce (PS = 1, LL = 0.133), and 5) Scenario X: no PS effort while keeping LL effort unchanged (PS = 0, LL = 1).

If we apply the harvest strategy based on the analytical results suggested by the equations, we could increase the SBR from 0.12 to 0.19 without cutting the fishing efforts by 20.5% for both purse-seine and longline fishing effort, as the IATTC implemented during 2009–2011. However, if we follow the harvest strategies specified in Scenario C, i.e. a disproportionally effort control between PS and LL, there is a net gain compared to Scenario B, such as the IATTC implemented policy during 2009–2011.

Table 2 presents the trade-offs of the five scenarios. Please note that the trade-off value under the different scenarios in Table 2 are not a direct result from the trade-off equations (1)–(7). First, Table 2 presents the revenue in a long run equilibrium as reducing PS catch will result in increase of LL bigeye catch, such as one ton of bigeye tuna not caught in the purse-seine fishery might give longline fishery a chance to catch 3.85 tons more in the long run. In addition, Table 2 only accounts for actual landings, while discards (as part of weight) are included in equations (1)–(7).

Scenario A in Table 2, the steady-state total revenue (which means no change to the 2008 levels of fishing effort for PS and LL, and SBR equals 0.12) would be lower than Scenario B (the 20.5% proportional reduction of both purse-seine and longline fishing effort). Scenario B shows that the SBR would increase from 0.12 to 0.19 and produce greater catches of bigeye, with greater values, by longliners. As discussed previously, PS fishing gear selects smaller tunas than longline gear. Reducing PS effort would allow bigeye to grow larger, thus yield per recruit increases, and fishery productivity increase.

The SBR = 0.19 curve can be used to evaluate a range of effort allocation schemes to obtain the biomass target. Scenario C shows if the longline effort is fixed at its 2008 level, the purse-seine effort would have to be reduced by 26.7% of its 2008 level, the net economic gains for both gears is $93 million, as compared to an equal proportional reduction, such as indicated by Scenario B, shown in Table 2.

For example, under Scenario C, compared to Scenario B in Table 2, the revenue gain of landing bigeye tuna for LL fleet will be $58 million, and the revenue loss of landing bigeye tuna for PS fleet will be $3 million, so the total net gain will be $55 million for the sum of the two fisheries.

By comparing Scenario C to Scenario B, the extra revenue generated by the longline fleet would be $58 million in bigeye tuna catches, and $57 million in yellowfin tuna catches. For the purse-seiners, there would be $3 million, $11 million, and $8 million decreases in the catches of bigeye, yellowfin, and skipjack, respectively. The increase in revenue to the longline fishery—$115 million—would far exceed the decrease in revenue to the purse-seine fishery—$22 million. Scenario X generates the greatest catches of bigeye with greater values, by longliners, if PS fisheries could avoid catching any juvenile bigeye tuna in the long run.

The worst scenario in terms of the total economic value for the sum of two fisheries is maintaining the purse-seine effort at its 2008 level while reaching the goal of the SBR at 0.19 (Scenario D), with the longline effort reduced to 13.3% of its 2008 level. In this case, society would experience a $311 million loss or 25% reduction in total revenue,

Table 2
Static comparison of the retained bigeye and yellowfin tuna retained catches landed by longline and purse-seine landings and value under different scenarios while holding the SBR as 0.19.

Fishery Scenario/Species	Landings by Species		Revenue by Species (million US$)					
	LL	PS	LL	Compared to Scenario B	PS	Compared to Scenario B	Total	Compared to Scenario B
	(1000 mt)							
Bigeye Tuna								
A	22	59	211		93		304	–
B	**27**	**56**	**263**		**89**		**352**	-
C	34	55	321	58	86	−3	407	55
D	4	62	41	−222	97	8	138	−214
X	99	0	948	685	0	−89	948	596
Yellowfin Tuna								
A	20	252	155		432		587	–
B	**22**	**245**	**173**		**418**		**591**	-
C	29	238	230	57	407	−11	637	46
D	3	262	23	−150	448	30	471	−120
X	109	0	849	676	0	−418	849	258
Skipjack Tuna								
A	–	220	–		313		313	–
B	-	**213**	-		**303**		**303**	-
C	–	207	–	–	295	−8	295	−8
D	–	228	–	–	325	22	325	22
X	–	0	–	–	0	−303	0	−303
All Tuna Total								
A	42	531	366		838		1204	
B	**49**	**514**	**436**		**810**		1246	-
C	63	500	551	115	788	−22	1339	93
D	7	552	64	−372	870	60	934	−312
X	208	0	1797	1361	0	−810	1797	551

*The standardized purse-seine and longline effort is indicated in the parenthesis under each scenario as Scenario A (PS = 1, LL = 1), Scenario B (PS = 0.795, LL = 0.795), Scenario C (PS = 0.737, LL = 1), Scenario D (PS = 1, LL = 0.133) and Scenario X (PS = 0, LL = 1).

relative to Scenario B.

3.3. *Dynamic (short-term) trajectory of recovery path of bigeye tuna under various policy options and projections of total landings and value*

The third model evaluates the dynamic (short-term) trajectory of recovery path of bigeye tuna under various policy options. Under current effort levels (Scenario A), the bigeye population is predicted to continue declining (Fig. 4). If the effort is reduced to levels that support an SBR of 0.19 under scenarios B, C, and D, the bigeye population is predicted to increase recruitment to higher levels than seen in recent years, and SPR under all three scenarios would reach the targeted long run equilibrium point at 0.19 starting from 2018. However, in comparison, the economic value of the catch would reach steady-state differently under a different scenario. Practically, for Scenario D, there would be a precipitous decline in 2009, followed by a gradual decline after that (Fig. 5). It shows that it would be impossible to maintain the total landings value in the long run if PS fleet is maintained at the current effort levels.

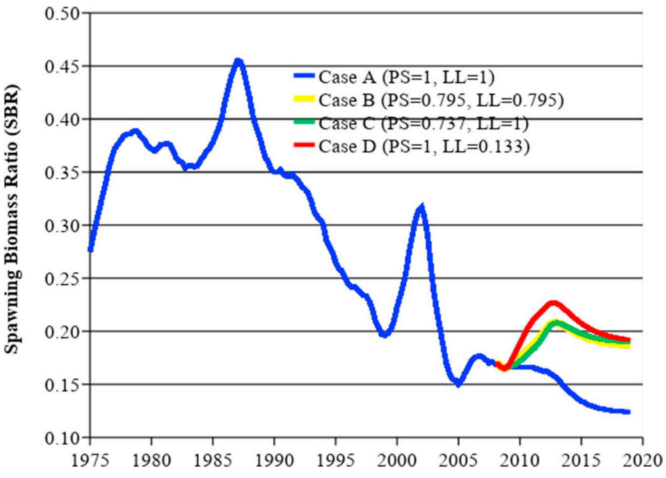

Fig. 4. Trajectory plot of bigeye tuna spawning biomass ratio under different floating objects purse-seine (PS) and longline effort (LL) levels relative to effort levels in 2008.

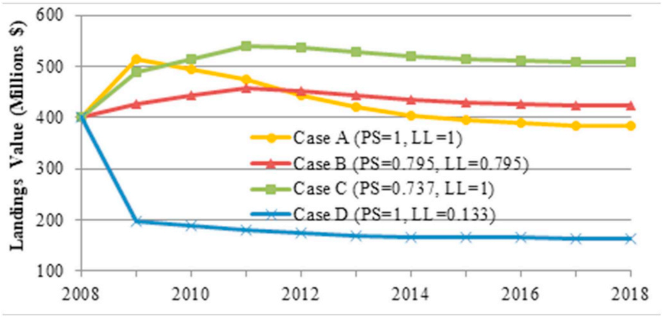

Fig. 5. Trajectory plot of total landings value of bigeye under Scenarios A, B, C, and D with different floating objects purse-seine (PS) and longline effort (LL) levels relative to effort levels in 2008 while holding the bigeye tuna SBR as 0.19.

Reduction in purse-seine effort to the level that maintains the bigeye SBR at 0.19 would cause a reduction in the skipjack catch and its corresponding value (Fig. 6). Based on the average landings of 138,204 mt of skipjack caught in purse-seine sets on tunas associated with floating objects, such as indicated in the introduction section, during 2000–2007 (Anonymous, 2008), the estimated loss of skipjack value of landings is $40.4 million and $51.8 million, respectively, for 20.5% and 26.7% reductions in purse-seine effort on tunas associated with floating objects for Scenarios B and C, respectively.

In Scenario B, for which there are 20.5% reductions in both longline effort and purse-seine effort on tunas associated with floating objects,

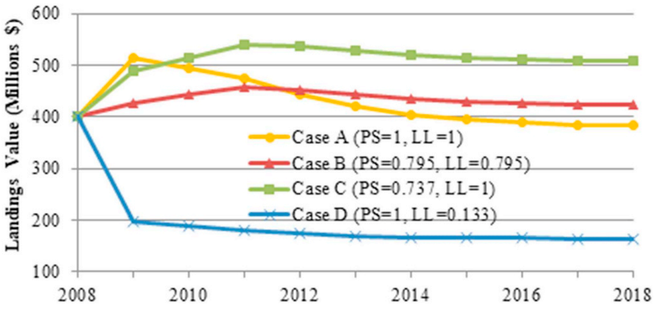

Fig. 6. Trajectory plot of the gains and/or losses of floating objects purse-seine (PS) and longline (LL) for each tuna species and the accumulated total landings value under Scenario B, C and D, while holding the bigeye tuna SBR as 0.19, compared to trajectory under Scenario A.

the cumulative loss due to reduced catches of skipjack would reach $200 million in three years. The increase in economic value due to the increase in the biomass of bigeye tuna and in the catch by longliners would not be enough to offset the loss due to the decreased catches of skipjack until 10 years later (Fig. 6: Panel (a)).

In Scenario C, we maintain the longline effort at the 2008 level and reduce the purse-seine effort on tunas associated with floating objects so that the SBR is maintained at 0.19. This combination produces higher total revenue for all years compared to the equal proportional reduction strategy in Scenario A.

By comparing Scenario C to Scenario A (Fig. 6, Panel (b)), total revenue is estimated to be reduced in the short term, but within 3 years it would be comparable to the level in Scenario A and would take only one more year to compensate for the initial loss in revenue during the first two years. After deducting the losses to purse seiners of catches of skipjack associated with floating objects, the cumulative gain in revenue to longline-fishing countries, who benefit from the recovery of the bigeye biomass, could be more than $800 million in 10 years.

As shown in Table 3, the cumulative value of the dynamic projections of the catches of bigeye and skipjack tuna by longliners and by purse seiners directing their effort toward tunas associated with floating objects under Scenario C would be $698 million greater than that for Scenario B during 2009–2018.

4. Policy implications

From the scenario analyses in the previous section, this study demonstrated that tuna in the EPO are not managed optimally with respect to their economic value. Catch and economic value are highly sensitive to the allocation of effort between the purse-seine and longline fisheries. Substantially greater total revenue for the EPO tuna fishery can be obtained by modifying the amount of effort attributed to the purse-seine fishery, which land majority of juvenile bigeye, and the longline fleets. For the same bigeye tuna biomass target levels, higher economic value can be obtained by increasing the longline effort and reducing the purse-seine effort. The policy implemented in 2009 (IATTC, 2009), which reduces both longline and purse-seine fishing effort proportionally so as to maintain the SBR of bigeye at = 0.19, results in a cumulative loss in value. This study suggests an alternative action that would reduce only the purse-seine fishing effort (26.7% instead of 20.5%) while keep the longline effort at the same level to maintain the SBR of bigeye at 0.19 would result in a substantial gain in value relative to 2008. These results suggest that the economic value should be an important consideration in the management of tropical tuna in the EPO.

Under the effort scenario that optimizes equilibrium economic value while holding longline effort constant (which reduces the influences of the unknown costs of fishing on the calculations) and reducing the purse-seine effort on tunas associated with floating objects, we estimate that total revenue would decline in the short term, but still retain a greater value than the proportional reduction scheme. Importantly, it would take only 3 years for total revenue to return to 2008 levels. In the steady-state equilibrium situation, the total annual revenue for the entire tuna fleet in the EPO would be $93 million greater annually based on the 2008 levels after compensating purse-seiners for their initial loss in revenue.

However, managing the fisheries for highly migratory species is complicated. Management objectives differ among resource users, and there are a multitude of factors that need to be considered. Economic value is given in terms of landed value and does not take into consideration the costs of fishing which may influence the calculation of economic value at the effort levels specified in this study. However, the influence of the cost of fishing can be reduced by maintaining 2008 effort levels in the longline fishery while reducing the purse-seine fishing effort. In this scenario, the additional cost to the longline fishery is only the cost of handling more fish, while the reduction in the cost of the purse-seine fishery would be substantial. However, allocation of effort among the fleets is complicated by the international composition of the fleets. In general, the large longline vessels are from distant waters in Asia. Smaller longline vessels from Hawaii also went to EPO for tuna fishing, while the purse-seine vessels are primarily owned by companies in Latin America and Europe. In addition, there are large numbers of artisanal longline vessels based in Latin America. An equitable approach is needed to allocate effort among the different fleets and nations to have the different counties/fisheries agree on the policy. The methods for doing this are discussed below.

1. Property rights. A property rights system that provides a quota to each fleet or nation based on some equitable scheme (e.g. historical catch or adjacency to the resource) and leaves the allocation of effort to the market could be developed. If our calculations are correct, the longline fleet should have the incentive to lease or purchase the quota from the purse-seine fleet because the longliners could get more value out of the same amount of quota. To avoid overexploitation due to differences in the age structure of the catch among fleets, a quota equivalency would need to be determined between longline and purse-

Table 3
Cumulative landings value of the dynamic projections of the retained bigeye and skipjack tuna landed by longliners and floating objects purse-seiners under different scenarios during 2009–2018.

Scenario	Floating Objects Purse-Seine				Longline		Total Value =(3)+(4)	Compared to Scenario B
	Bigeye Value (1)	Skipjack Value (2)	Total Value (3)=(1)+(2)	Compared to Scenario B	Bigeye Value (4)	Compared to Scenario B		
A	1278	1969	3247		3421		3247	
B	**1215**	**1566**	**2781**		**3545**		**2781**	
C	1170	1451	2621	−160	4403	858	3479	698
D	1321	1969	3290	509	812	−2733	557	−2224

Unit: Cumulated landings value (Million $).

seine fleets. Since there is a linear relationship between SBR and effort and this relationship appears to be similar for different target levels of SBR, an equivalency of 1 purse-seine quota equals 3.86 longline quotas would be appropriate. Setting quota in terms of effort would require strict controls on the effort standards. Setting quota in terms of amounts of fish caught would require accurate estimates of sustainable yields on an annual basis due to the variable nature of tuna populations.

2. Compensation. A compensation system could be used to pay the purse-seine fleet to reduce its fishing effort. The payment would have to be negotiated between PS and LL fleets, but the calculations here can determine a value that would be obtained by reducing the purse-seine catch. While holding bigeye SBR at 0.19, the marginal effect of increasing the steady-state equilibrium landings value for each ton of purse-seine bigeye tuna not caught is $36,878 and would reach a net value of $35,340 after providing $1540 compensation to the loss of purse-seine's bigeye tuna landings value. The longline fishery could compensate the purse-seine fishery for their decreases in revenue and still be better off than they are at present, economically.

Considering all three major tuna species, the economic value would be increased by $93 million if the managers were to allow the longline fleet to maintain its effort at the 2008 level without increasing its expenditures (Table 2). The purse-seine fleet would decrease its expenditures while maintaining its income (sales of fish caught plus payments from longline interests), so its benefit would be even greater.

If the purse-seine vessels were paid an amount equal to the value of their catch to reduce fishing effort, while the longline effort is fixed at its 2008 level, the purse-seine effort would need to be reduced to 73.7% of its 2008 level to achieve the bigeye tuna SBR of 0.19. In contrast, IATTC recommendation, at the time of this analysis, was that there be 20.5% reductions in both the purse-seine and longline efforts. The additional cost for reduction of only the purse-seine effort would be $8 million, but the increase in revenue to the longline fleet would be $102 million, for a net economic increase of $93 million. In addition, the costs to the purse-seine fleet of maintaining the vessels in port would be far less than the costs of fishing, further increasing their benefits.

3. Bycatch compensation. It is possible that purse-seine vessels could reduce bigeye catches in sets on tunas associated with floating objects, although preliminary studies (Lennert-Cody et al., 2008) suggest that this may be technically difficult. The purse-seine vessels would be allowed to capture skipjack and yellowfin tuna, while catching fewer bigeye. A technically possible compensation scheme could be used to pay purse-seine vessels to avoid bigeye tuna, as doing so may reduce their efficiency. Bycatch avoidance may also increase costs due to additional man power or equipment needed.

4. Vessel buybacks. A vessel buyback system (Lennert-Cody et al., 2008; Allen et al., 2010), in which the longline fishery purchases purse-seine vessels and converts them to other uses, could be implemented. Strict control would be needed to ensure that no new purse-seine vessels entered the fishery. Currently, the IATTC has a limit on the fish-carrying capacity of purse seiners that are permitted to fish in the EPO (Joseph et al., 2010). The fish-carrying capacity (which is approximately proportional to fishing capacity) of the purse-seine fleet in the EPO was 209,000 m^3 in 2009. Based on data given by Allen et al. (2008, 2010), the prices paid for a used vessel with 1200 m^3 fish carry capacity ranged between $5 million and $8.5 million, so the estimated cost of reducing the capacity to 73.7% of its 2008 level (Scenario C), which would support the bigeye tuna SBR of 0.19, is $229 million to $366 million. The cost of buying back all the purse-seine vessels would be $871 million to 1393 million, which is roughly equivalent to the gain in Scenario C after cumulative the annual gain for ten year.

The vessel buyback proposal would be a one-time cost and would occur either in a single year or over several years. If carried out over several years, it would take longer for the benefits to be realized compared to paying the purse-seine vessels not to fish. Care would be needed to determine the effective fishing capacities of the vessels purchased, since the least efficient vessels could be the first to be offered for sale. The buyback would work based strictly on vessel costs if the purse-seine fishery was not making a profit, otherwise the business value of the vessel (the fact that it has fishing access to the EPO) would also have to be integrated into the purchase price.

If the compensation system paid the purse-seine fleet to reduce its fishing effort, the annual revenue of the longline fishery would increase by $93 million after compensating for the losses in revenue to the purse-seine fishery, by allocating the effort in accordance with Scenario C, rather than continuing with Scenario B. It would take only 3–4 years to accumulate enough funds to buy back the 26.3% excess purse-seine capacity, and it would be even sooner if we planned to buy back only about 30% of the purse-seiners who set on floating objects.

5. Summary and discussion

The IATTC management measure, at the time of this analysis, which requires 20.5% equal proportional reductions in effort for both the purse-seine and longline fisheries is not economically optimal. Decreasing purse-seine effort can increase equilibrium economic value for the whole tuna industry while achieving the recovery target of bigeye tuna biomass level more efficiently. To lessen negative economic impacts and make the proposals described above more attractive to purse-seine fishing nations, potential agreements should consider more than just revenue. The longline nations could implement joint venture longline vessels or establish processing or transportation plants in nations that had their purse-seine fisheries reduced or eliminated.

The dynamic effect of the compensation scheme needs to be considered. It would take several years before the stock can rebuild allowing and longline catches to increase. Therefore, the preliminary strategy would lower the value of the longline fleet. However, this loss would be recovered after 2–3 years. Any agreement would have to cover a substantial number of years to ensure that benefits properly accrue to the longline fleet.

Spawning biomass would also increase under scenarios that reduce the purse-seine effort and keep the longline effort at 2008 levels. This would provide additional protection against stock collapse. In addition, the calculations made above assume that recruitment is independent of stock size, if the SBR is equal to or greater than 0.19. If recruitment increased with stock size, the value of the fishery would be expected rise as well. Additionally, catches of yellowfin in the longline fishery might increase if longline vessels change their practices to target yellowfin.

The calculations in this paper are based on several assumptions about the population dynamics of bigeye, yellowfin, and skipjack, and their economic value. There are situations in which the increase in value could be overestimated, and this needs to be taken into consideration when contemplating the suggested actions. For instance, our calculations do not consider the elasticity of the market as increased longline catches of bigeye might reduce the price received in sashimi markets (Sun and Chiang, 2010). Additionally, it is not certain that all bigeye that are vulnerable to the purse-seine fishery would be vulnerable to the longline fishery. For example, the large increase in purse-seine catches of bigeye tuna as the floating object fishery expanded did not appear to reduce the longline catch rates as might be expected, indicating the possibility that though bigeye are vulnerable to the purse-seine fishery, they may not be vulnerable to the longline fishery. Initially, the longline effort covered the area in the equatorial eastern part of the EPO, now fished by the purse seine fishery, but the longline effort in this area has greatly reduced since the expansion of the purse seine fishery on floating objects. Substantial movement of juvenile tunas from the central Pacific Ocean into the EPO has been identified from tagging data (Schaefer et al., 2015), and this may influence the results of this study. However, there is little movement data for adults and therefore a reliable spatial model is not available to determine the impact of a Pacific-wide stock. More data on movement would allow spatial modelling and a better determination of the interaction between the purse seine fishery and the longline fishery as well as the impact of movement between the WCPO. Alternatively, experiments with reduced purse seine effort for several years could be used to see if the catch in the longline fishery increased.

We have shown that the economic value of the resource is highly dependent on the allocation of effort between the longline and purse-seine fisheries. Economic and social considerations were not formally integrated into management of the fisheries for tropical tunas in the EPO until 2010 when the new IATTC convention stated that "Considering the importance of fishing for highly migratory fish stocks as a source of food, employment and economic benefits for the populations of the Parties … conservation and management measures must address those needs and take into account the economic and social impacts of those measures (IATTC, 2010)." The details of a management system that gives equal weight to economic value require considerable exposition, but the potential benefits of implementing such a system should not be ignored.

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