Bioeconomic losses from overharvesting tuna

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Abstract

Stochastic dynamic programming is used to model the world's largest fishery—tunas of the western and central Pacific—and to show that adopting a biomass target that maximizes the discounted economic profits (B_{MEY}) from harvesting would result in larger stocks compared to de facto biological targets, and also lower catches relative to business as usual. This result is obtained for the three major tuna species, including skipjack tuna, which is not currently considered to be overfished biologically. Gains from larger tuna stocks are shown to exceed US$ 3 billion and increase the likelihood of stock rebuilding as some of these higher profits could be used to compensate fishers and countries for transitional losses to higher biomass levels. Adopting a dynamic B_{MEY} target thus offers a potential "win-win"—better conservation outcomes with larger fish stocks and higher economic profits.

Introduction

Key questions in the sustainable management of fisheries are: What should be the target biomass? How can fisheries be managed to move toward such a target? When should these targets be achieved if stock rebuilding is required? For decades fisheries managers have adopted a maximum sustained yield biomass (B_{MSY}) as their target (Anderson *et al.* 2008), or used it as a limit reference point. As biological biomass targets are independent of profits, fishers frequently oppose stock rebuilding designed to achieve desirable biological reference points.

Recent modeling shows that a biomass target that maximizes the sum of the discounted net profits from fishing—the dynamic maximum economic yield biomass (B_{MEY})—will, under reasonable discount rates, exceed B_{MSY} in some fisheries (Grafton *et al.* 2007). Factors that favor this result include a high intrinsic growth rate, a low discount rate, and the importance of stock abundance (i.e., a "stock effect") and fishing effort on the level of harvest. Using biological and economic data from the one of the world's most valuable fisheries—the Western and Central Pacific tuna fisheries (WCPTF)—we extend Grafton *et al.* (2007) to account for both transitional and ongoing payoffs and calculate measures of economic profitability from adopting a dynamic B_{MEY} target versus business-as-usual.

The main target species in the WCPTF include: skipjack tuna (*Katsuwonus pelamis*) caught mainly by purse seine vessels, yellowfin tuna (*Thunnus albacares*) caught by both purse seine and longline vessels, and bigeye tuna (*T. obesus*) caught predominantly by longline vessels (Williams & Reid 2006). The total harvest across all species has increased, on average, by about 5% per year over the

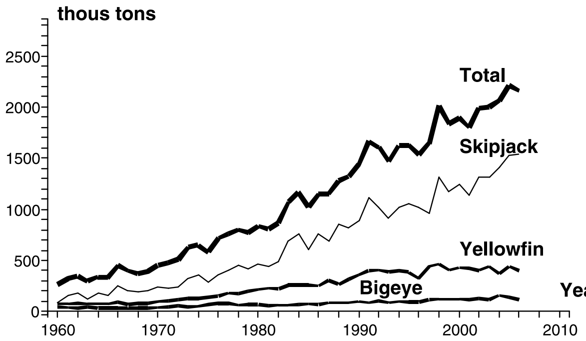

Figure 1 Catches of bigeye, yellowfin, and skipjack tuna (1960–2006).

past 50 years (Figure 1), but fishing effort has grown even faster with the total number of boat-days rising at an annual rate of about 10% per year over the period 1970–2000.

The WCPTF are collectively managed by member countries of the Western and Central Pacific Fisheries Commission (WCPFC). The multilateral compliance measures of the WCPFC include a compulsory vessel registry for fishing vessels, a vessel monitoring system that tracks their location, some observer coverage to record catches and, most recently, a scheme that tries to cap the total number of vessel days by purse seine vessels operating in the region.

A biological justification to limit fishing effort of yellowfin and bigeye has been consistently been made by the Scientific Committee of the WCPFC. Despite an acceptance of the conclusions of the Scientific Committee, key recommendations to reduce catches of yellowfin and bigeye have not yet been implemented (Langley *et al.* 2009). This is because many fishers, and some countries, do not consider it is in their economic interest.

To prevent further declines in profitability and to promote the sustainability of tuna stocks, at a minimum, demands that WCPFC members understand the bioeconomic costs of business-as-usual. An analysis of these costs requires: (1) dynamic B_{MEY} targets for the main tuna species; (2) optimal transition paths in terms of the total catches of tuna over time to achieve dynamic B_{MEY} targets; and (3) calculation of the bioeconomic losses from business-as-usual compared to profits at the dynamic B_{MEY} targets.

Methods

To calculate the dynamic B_{MEY} target for the major tuna species and the corresponding bioeconomic losses, a suitable biological model must be developed and connected to an economic model. Bertignac *et al.* (2000) provided one of the first estimates of profits in the fishery and estimated the effects of changes in fishing effort across countries. Reid *et al.* (2006) constructed a useful bioeconomic model of the fishery but did not provide optimal results, measures of dynamic B_{MEY} or bioeconomic losses from not pursuing the path to B_{MEY} or its target. Kompas & Che (2006) and Grafton *et al.* (2007) developed dynamic B_{MEY} results for the fishery but did not generate path to B_{MEY} effects, or the transitional losses from not following a path to B_{MEY}.

The biological structure and the parameters in the dynamic bioeconomic model in this article are based on Hampton *et al.* (2006a, b). Quarterly cohort structures in an age-structured model are developed where the initial size of the cohorts is determined by current recruitment, after which time cohort attrition occurs due to natural and fishing mortality. The dynamic growth of each species by each cohort is modeled at quarterly time steps. Recruitment is the appearance of age-class "one" fish in the population and it is assumed that recruitment occurs instantaneously at the beginning of each quarter, following a Beverton Holt stock recruitment relationship (discrete approximation) with coefficients by species and regions based on Hampton *et al.* (2006a, b).

Assumptions made concerning age and growth are: (1) lengths-at-age are normally distributed for each age-class; (2) mean lengths-at-age follow a von Bertalanffy growth curve; (3) standard deviations of length for each age-class are a log-linear function of the mean lengths-at-age; and (4) the distribution of weight-at-age is a deterministic function of the length-at-age and a specified weight–length relationship. The natural mortality rate (m) is assumed to be age specific, invariant over time and region, and continuous through the time steps. The current biomass, the virgin biomass, and the current rates of exploitation of each species are estimated as the average for 2001–2004 from Hampton *et al.* (2006a, b) with time-series biomass data from Hampton *et al.* (2006a).

Biological model

Let $B(t+1)$ denote the fish biomass (measured in weight) at time $t+1$ be given by

$$B(t+1) = [B(t) - h(t)]e^{\delta(B(t))} + f[B(t)] 0 \leq h(t) < f[B(t)] \tag{1}$$

where $B(t)$ is the previous period's biomass, $h(t)$ is the fishing mortality, $d(B(t))$ is the net growth of fish biomass, and $f[B(t)]$ is the growth function of fish biomass.

The population dynamic of fish biomass or recruitment ($R(t)$) is measured in weight and is given by

$$f[B(t)] = R(t) = \frac{\mu_3 B(t)}{1 + \mu_4 B(t)} \tag{2}$$

where μ_3 and μ_4 are the parameters of the Beverton–Holt model (Beverton & Holt 1957).

The net growth of fish biomass $\delta(B(t))$ is determined by

$$\delta(B(t)) = g(B(t)) - m(B(t)) \tag{3}$$

where $g(B(t))$ is the growth function of the biomass measured in weight from period t to $t + 1$, which depends on the size of $B(t)$ and the growth length–weight relationship; $m(B(t))$ is natural mortality which depends on the natural mortality rate, m, and the size of $B(t)$ and is allowed to vary by age cohort.

Based on the stock assessment, a conversion from fish numbers to weight is required and obtained from a standard growth in length and length–weight relationship given by a von Bertalanffy formula (1938). The growth in fish length is

$$l_t = l_\infty \left[1 - e^{-k(t-t_0)}\right] \tag{4}$$

where l_∞ defines an asymptotic or maximum body size, k_i is the Brody growth coefficient, defining the growth rate toward the maximum, and t_0 shifts the growth curve along the age axis to allow for apparent nonzero body length at age zero. The length–weight relationship is thus

$$w_t = u\,[l(t)]^v \tag{5}$$

where u and v are parameters.

Finally, the $\delta(B(t))$ component of the net growth of fish biomass in (1) depends on the natural mortality, m, and fish density, $(B(t)/B(0))$. The lower is fish density the higher is net growth. At maximum density (or $B(t) = B(0)$) the net growth of the biomass is at minimum. The functional relationship of the net growth in the biomass is given by

$$\delta(B(t)) = \psi \left(\frac{B(t)}{B(0)}\right)^{\chi} \tag{6}$$

where ψ and χ are parameters and ψ is estimated from $R(0)$ and $B(0)$. The biological model is not explicitly spatial except that it corresponds to the established zones specified in the WCPO tuna regions. Additional information on the biological model is contained in the supporting information.

Bioeconomic model

At a given time t ($t = 1, \ldots, T$), the harvest is denoted by h_{ijg} that indicates the harvest of species i by fleet j in area g where $i = 1, 2, 3$; $j = 1, \ldots, 12$; and $g = 1, 2, 3$, i.e., there are 3 species, 12 fleets, and 3 fishing areas or zones. The harvest function of a species i by fleet j in area g at time t is given by

$$h_{ijg}(t) = q^0_{ijg} E^{\alpha_{ijg}}_{ijg}(t) B^{\beta_{ijg}}_{ig}(t) \tag{7}$$

where q^0_{ijg} is the intercept term; $E_{ijg}(t)$ is the effort of fleet j to fish species i in area g; $B_{ig}(t)$ is the biomass stock of species i in area g; and α_{ijg} and β_{ijg} are the parameters of the harvest function of fleet j for species i in area g.

The fishing effort of fleet j is measured as total effort for all species in all areas averaged over tuna caught with fishing aggregating devices and with unassociated sets. The effort allocation to a species i in area g is

$$E_{ijg}(t) = \theta_{jg}\theta_{ij} E_j(t) \tag{8}$$

where θ_{jg} is the regional effort share of fleet j to each fishing area with the constraints

$$\sum_{g=1}^{3} \theta_{jg} = 1 \quad \text{and} \quad \sum_{i=1}^{3} \theta_{ij} = 1 \tag{9}$$

The coefficient θ_{ij} in (8) indicates that the effective effort allocation among species of fleet j also influences the effective fishing effort on other species, where these other species can be targeted by the same unit of nominal effort.

Total revenue of fleet j at time t (TR_{jt}) is defined as a sum of all revenues (the product of harvest and average price) over all species and areas, i.e.,

$$TR_j(t) = \sum_{g=1}^{3}\sum_{i=1}^{3} TR_{ijg}(t) = \sum_{g=1}^{3}\sum_{i=1}^{3} h(t)\,p_{ij}(t) \tag{10}$$

where $p_{ij}(t)$ is the price of species i caught by fleet j at time t. Output prices for species differ depend on the market where fish is sold, based on the analysis by Reid *et al.* (2003, 2006) and the Forum Fisheries Agency (2008). Fish prices used in this article are analyzed separately for the canned tuna and sashimi market.

Price elasticity measures the responsiveness of the quantity demanded of fish to a change in price that arises from a change in harvest brought to market. Price elasticities differ between the canned tuna and the fresh and frozen market. For the frozen and fresh markets, the price elasticity of demand (ε) for bigeye is 10 so that a 1% rise in quantity supplied to market causes a 0.1% fall in its price, and for yellowfin $\varepsilon = 6.5$. For the canned market the elasticity for skipjack is 1.9 for supply increases and 11.1 for supply decreases and is based on estimates by Pan & Pooley (2004). Further details are provided in the supporting information.

Fishing cost (including labor, material, capital, and all other costs) is a function of fishing effort defined by

$$c_{ijg}(t) = \gamma^0_{jg} + \gamma^1_{jg} E_{ijg}(t) \tag{11}$$

where γ^0_{jg} and γ^1_{jg} are the fixed cost and variable cost parameters.

Combining Equations (7) to (11), the profit function of fleet j at time t fishing species i in area g ($\Pi_{ijg}(t)$) is defined by

$$\Pi_{ijg}(t) = p_{ij}(t)\left[q^0_{ijg}E^{\alpha_{ijg}}_{ijg}(t)B^{\beta_{ijg}}_{ig}(t)\right] - \left[\gamma^0_{jg} + \gamma^1_{jg}E_{ijg}(t)\right] \tag{12}$$

Total profit of fleet j at year t ($\Pi_i(t)$) is a sum of all species over all areas, or

$$\Pi_j(t) = \sum_{g=1}^{3}\sum_{i=1}^{3}\left\{\left[p_{ij}(t)\left(q^0_{ijg}E^{\alpha_{ijg}}_{ijg}(t)B^{\beta_{ijg}}_{ig}(t)\right)\right] - \left[\gamma^0_{jg} + \gamma^1_{jg}E_{ijg}(t)\right]\right\} \tag{13}$$

Aggregate profit of the WCPO across all tuna species, all fleets, and all fishing areas at time t ($\Pi\ (t)$) until period T is thus:

$$\Pi = \sum_{t=1}^{T}\sum_{j=1}^{12}\sum_{g=1}^{3}\sum_{i=1}^{3}\left\{p_{ij}(t)\left[q^0_{ijg}(\theta_{ig}\theta_{ij}E_j(t))^{\alpha_{ijg}}B_{ig}(t)^{\beta_{ijg}}\right] - \left[\gamma^0_{jg} + \gamma^1_{jg}(\theta_{ig}\theta_{ij}E_j(t)\right]\right\} \tag{14}$$

where $E_{ijg}(t)$ is substituted from $E_j(t)$ as indicated in (8).

Optimization problem

The optimization problem used to calculate optimal fishing effort and dynamic B_{MEY} maximizes the sum of expected aggregate profits through the choice of effort for each fleet, by nation, for each species in each fishing area over the planning horizon, i.e.,

$$\max_{E_j(t),\,\theta_{ij}} \Pi = \sum_{t=1}^{50}\frac{1}{(1+r)^t}\sum_{j=1}^{12}\sum_{g=1}^{3}\sum_{i=1}^{3} \times \left\{p_i(t)\left[q^0_{ijg}(\theta_{ig}\theta_{ij}E_j(t))^{\alpha_{ijg}}B_{ig}(t)^{\beta}_{ijg}\right] - \left[\gamma^0_{jg} + \gamma^1_{jg}(\theta_{ig}\theta_{ij}E_j(t)\right]\right\} \tag{15}$$

where r is the discount rate and the objective function is maximized subject to (1), (7), (9), and

$$h_{ig}(t) = \sum_{j=1}^{12} q^0_{ijg}E^{\alpha_{ijg}}_{ijg}(t)B^{\beta_{ijg}}_{ig}(t) \tag{16}$$

The value θ_{ij} is the choice variable that determines $E_{ij} = E(t)\ \theta_{ij}$ and the optimal effort allocation to species i and fleet j. Uncertainty is added to the model in two ways: (1) by including a diffusion term in the stock transition Equation (2) of the form $\sigma B(t)\kappa_t$ for realization κ_t drawn from a normal distribution with variance $\sigma = 0.05$; and (2) by including the standard errors in the point estimates for α_{ijg} and β_{ijg} in the harvest function, or Equation (7). All reported monetary values are thus expected values conditional on the form of uncertainty. To save on notation and the complexity of the relevant expressions, these terms are not explicitly added to the equations. The supporting information reports the estimates of the harvest function.

After including random variation in relevant variables (i.e., the standard errors in coefficient values drawn from estimates of the harvest function by region) and a diffusion process for the biomass it is not possible to find an analytical solution to (15). Instead, the solution is obtained using a perturbation method (see Judd (1998)) to maximize the value function given by (15), subject to (1), (7), (9), and (16), accounting for the potential "stock effect" implied by the nonlinear harvest function. It is the stock effect (implying that either harvest or costs are stock dependent) that ensures that the dynamic version of B_{MEY} coincides with stock values that are larger than stock at B_{MEY}, with the share coefficient on the stock term in the harvest function, or β_{ijg}, determining a "marginal stock effect." A terminal condition is chosen so that discounted profits become zero at the terminal point. The planning horizon for the optimization procedure is chosen to ensure that the optimal path maximizes profits over a sufficiently long period of time (i.e., what in a deterministic model would be a near steady state) before stocks are drawn down to satisfy the terminal condition. All results are drawn from the resulting optimal path.

Parameter values

To implement and solve the problem specified by (15), and the associated constraints, we use previously estimated or calculated biological and price parameters, and specifically estimated (see the supporting information) parameters for the harvest function (q^0_{ijg}, α_{ijg}, and β_{ijg}). Selected estimates for the purse seine fleet and the longline fleet are provided in Table 1. Cost parameters of fleet j in area g, denoted by γ^0_{jg} and γ^1_{jg}, are provided in Table 2, and are based on Reid *et al.* (2003) and Reid *et al.* (2006). Additional information is contained in the supporting information.

Results

To calculate the bioeconomic losses from business as usual versus managing the fisheries at their dynamic B_{MEY}, we employ a planning period of 50 years, with base the year 2006, but project our model with starting values from 2008, applying a discount rate of 5%. (See Gault *et al.* (2008) on the problematic use of discount rates with highly valued natural resources.) In the base year, total expected profits for purse seine, frozen longline and fresh longline fleets are calculated at \$93 million, \$120 million, and \$109 million dollars (in 2008 prices) and levels of

Table 1 Parameter estimates of the harvest function (biomass estimates to 2002, variable years by zone, from 1972, see supporting information)

	Yellowfin	Bigeye	Skipjack
Purse seine fleet (zone 3)			
Intercept (*q*)	−0.55	−1.59*	−0.21
Fishing effort (*E*)	0.90***	0.61***	1.09***
Biomass (*B*)	0.23*	0.58	0.15*
Purse seine fleet (zone 4)			
Intercept (*q*)	−7.29***	−9.31**	−0.78
Fishing effort (*E*)	1.30***	1.36***	1.10***
Biomass (*B*)	1.14**	1.56*	0.21
Longline fleet (zones 3 and 4)			
Intercept (*q*)	−1.96	−1.79	
Fishing effort (*E*)	0.71***	0.65***	
Biomass (*B*)	0.45*	0.40*	

Notes:
1. Fishing effort defined in vessel days for the purse seine fleet.
2. Fishing effort defined in thousand hooks for the longline fleet.
3. Biomass defined in tonnes.
***Statistically significant from zero at 1% level of significance.
**Statistically significant from zero at 5% level of significance.
*Statistically significant from zero at 10% level of significance.

fishing effort in all other periods are compared to the effort levels in 2006 (100 = effort level in 2006).

Fishing effort

Table 3 summarizes the differences between the base year and dynamic B_{MEY} target effort levels in the first 5 years (2008–2012) and when the B_{MEY} target has been achieved. It also compares the dynamic B_{MEY} target with B_{MSY}—the default biological reference point for the WCPFC and dynamic B_{MEY} to the current biomass (B_{CUR}). The results show that in the first 5 years of the planning period (2008–2012) fishing effort for purse seine, frozen longline, and fresh longline needs to be reduced to 44%, 40%, and 51%, respectively, of their base levels. Important shifts in fishing effort between species are also required to maximize the sum of discounted economic profits from fishing over time.

Table 2 Fishing costs and fish prices by fleets and species (2006 prices US$)

Fleet	Cost parameter ($/effort unit)	Fish prices ($/ton)		
		Skipjack	Yellowfin	Bigeye
Purse seine (*$US/ day*)				
United States	24,415	544	1,270	1,806
Japan	29,271	564	1,669	2,375
Korea	23,841	513	842	1,197
Taiwan	17,772	513	842	1,197
PICs	11,669	513	842	1,197
Philippines and others	13,467	513	842	1,197
Frozen tuna longline ($US/hook)				
Japan	3.43		5,960	8,479
Korea	2.63		5,377	7,651
Taiwan	1.73		5,377	7,651
Philippines and others	1.44		5,377	7,651
Fresh tuna longline ($US/hook)				
Japan	2.11		5,377	7,651
China	1.44		4,071	5,792
Taiwan	1.73		8,437	12,004
PICs and others	1.70		4,071	5,792

Biomass

The results in Table 3 show that the dynamic B_{MEY} target is larger than B_{MSY} for yellowfin, bigeye, and skipjack tuna. This is because a larger biomass makes it easier to find and catch fish that lowers per unit harvesting costs and increases expected profits. Given the price elasticity of demand, a lower catch also increases the price of fish.

The finding that dynamic $B_{MEY} > B_{MSY}$ for all tuna species shows that although skipjack tuna is not currently overfished biologically, it is overexploited in an economic sense. Yellowfin tuna and bigeye tuna are overexploited in an economic sense because $B_{MEY} > B_{CUR}$ and are also overfished biologically because current fishing mortality exceeds the fishing mortality at B_{MSY} (Langley *et al.* 2009).

Sensitivity results on the values of B_{MEY} to B_{MSY}, in terms of changes in parameter values for the stock coefficient, average tuna prices, and the costs of fishing are reported in the supporting information.

Bioeconomic losses

The net expected present value of profits is the sum of the discounted annual expected profit from fishing in U.S. dollars and is calculated for each period in the 50-year planning horizon for two scenarios. The dynamic B_{MEY} scenario represents the optimal transition path to the dynamic B_{MEY} target while the business-as-usual scenario assumes that the base-year levels of fishing effort for each fleet are maintained. A comparison of the net present value of profits of the two scenarios across all tuna species for the 50-year planning period is presented in Figure 2.

Stock rebuilding associated with the transition to the dynamic B_{MEY} target results in initially lower profits compared to business-as-usual for the first 3 years. Thereafter, after the biomass of the tunas has increased, the transition to the dynamic B_{MEY} target generates higher expected profits than business-as-usual. The net present value of expected profits is maximized with the dynamic B_{MEY} target between 10 and 12 years. It declines thereafter because of the impact of discounting and *not* because of any reduction in the biomass or profitability in nominal

Table 3 Results for optimal solutions (discount rate = 0.05)

Fleet Type	Optimal effort level as % of base year value (= 100)	Optimal effort allocation across species		
		Yellowfin	Bigeye	Skipjack
Purse seine				
In the first 5 years	43.5	20.0	20.0	60.0
Steady state	46.1	24.7	23.6	51.7
Frozen longline				
In the first 5 years	39.9	41.3	58.6	
Steady state	55.2	44.6	55.4	
Fresh longline				
In the first 5 years	50.6	44.0	56.0	
Steady state	60.6	45.6	54.4	
Ratio	**Denotation**	**Yellowfin**	**Bigeye**	**Skipjack**
Biomass ratios				
Dynamic MEY biomass/ MSY biomass	B_{MEY}/B_{MSY}	1.19	1.80	2.47
Dynamic MEY/Current biomass	B_{MEY}/B_{CUR}	1.59	1.22	1.15

Notes:

1. The biological sources of B_{MSY} and B_0 are provided from Hampton *et al.* (2006a, b).
2. Dynamic MEY/Current biomass ratio based on business-as-usual projections for the current biomass to 2008 from a 2006 base year.

dollar terms. The integral of the areas between the two curves represents the bioeconomic losses from business-as-usual compared to adopting a dynamic B_{MEY} target.

If the tuna fisheries were managed according to the dynamic B_{MEY} target the cumulative expected net present value over the entire planning period is $5.4 billion or about $108 million per year. If the fishery follows the business-as-usual path (not including losses after year 35), the cumulative expected net present value with business-as-usual is $2.0 billion, or about $57 million per year. Thus, the bioeconomic losses from business-as-usual are approximately $3.4 billion. This result varies relative to sensitivity on parameter values as reported in the supporting information, from $1.9 to $4.8 billion, but the main point still stands. Business-as-usual results in large economic losses relative to optimal harvesting.

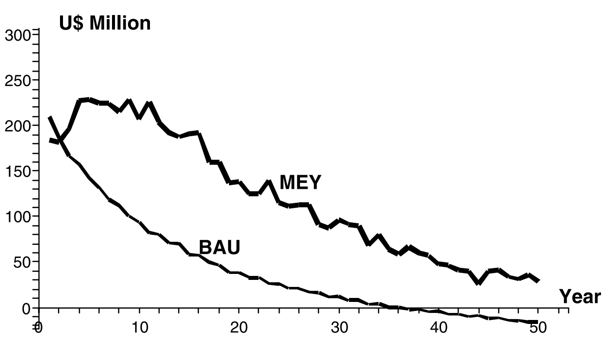

Figure 2 Net present value of profit (2008 prices in US$ millions) of dynamic B_{MEY} and business-as-usual transition paths.

Discussion

The results provide both an economic and a biological justification for reducing current fishing effort and increasing biomass levels of all tunas (including skipjack tuna) in the world's largest fishery. Higher future profits can be used to compensate fishers fully for initially lower harvests and net returns as stocks transition to higher biomass. Profits could also be used to finance transfers of funds to some countries, or possibly via the transfer of annual harvest allocations (Chand *et al.* 2003; Munro & van Houtte 2004; Grafton *et al.* 2010) to help ensure support for lower overall catches. A continuation of business-as-usual in the tuna fisheries will not only generate much lower profits relative to a dynamic maximum economic yield target, but will also jeopardize the conservation of yellowfin and bigeye tuna stocks.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

The supplementary material is arranged in the following sections: (1) Biological analysis, (2) Harvest function, (3) Effort and harvest, (4) Fish prices and costs, and (5) Optimization problem and sensitivity results.

Table S1: Harvest function of purse seine fleet in region 3 (1972–2002).

Table S2: Harvest function of purse seine fleet in region 4 (1983–2002).

Table S3: Harvest function of longline fleet for regions 3 and 4 (1990–2003).

Table S4: Price elasticity of demand by species and fleet.

Table S5: Fishing costs and fish prices by fleets and species (2006 US$).

Figure S1: MEY and BAU biomass for yellowfin tuna in region 3.

Figure S2: MEY and BAU biomass for yellowfin tuna in region 4.

Figure S3: MEY and BAU biomass for bigeye tuna in region 3.

Figure S4: MEY and BAU biomass for bigeye tuna in region 4.

Figure S5: MEY and BAU biomass skipjack in regions 3 and 4.

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