TUNA RESOURCE MANAGEMENT

Economic profit and optimal effort in the Western and Central Pacific tuna fisheries

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Given the problems with open-access resources, as well as the effectiveness of modern fishing technology, there are few international fisheries (if any) that will not be over-exploited and less than fully profitable unless they are managed effectively. For a fishery to be economically efficient, management targets must be set correctly, enforced effectively and delivered in a least-cost and incentive-compatible manner. An economically efficient outcome is important not only because it protects fish stocks and guarantees sustainability, but because it ensures that resources will be allocated correctly and in a way that maximises the returns from fishing over time (Grafton et al. 2006).

Solving a stochastic optimal control model in order to maximise discounted profits, across different regions, gear types and species in the Western and Central Pacific tuna fishery (WCPTF), this paper provides solutions for optimal effort levels and their allocation across species over a 50-year planning horizon. Solutions are obtained through a finite difference algorithm, using parallel processing software, for three main species in the fishery—yellowfin tuna, bigeye tuna and skipjack—and the most important gear types—purse-seine and fresh and frozen longline (Williams and Reid 2006). In order to maximise economic profits, results indicate that a substantial effort reduction is needed in the fishery for the three main species, with optimal stocks significantly larger than stocks at maximum sustainable yield (MSY) in all cases.

The WCPTF is diverse, ranging from small-scale artisanal operations in the coastal waters of Pacific states, to large-scale, industrial purse-seine, pole-and-line and longline operations in the exclusive economic zones (EEZs) of Pacific states and on the high seas. The fishery is one of the largest and most valuable tuna sources in the world, providing approximately 2 million metric tonnes per annum, or half of the global tuna supply equivalent (SPC 2006; Reid et al. 2003). The WCPTF plays an essential social and economic role in the region, contributing an annual average gross value of roughly US$3 billion a year in the past five years. Small Pacific island states in particular rely heavily on the WCPTF as a source of food and foreign currency, which is drawn from licence fees as well as exported product (Reid et al. 2003; Chand et al. 2003).

Previous studies

In the past three decades there have been substantial changes in the level and composition of fishing effort in the WCPTF. Accordingly, a number of studies have partially addressed the issue of optimal fleet composition. Campbell (1994) and Campbell and Nicholl (1995) examined the effect of a hypothetical marginal reallocation of the yellowfin tuna stock from the purse-seine to the longline fishery, and Hampton et al. (1997) modelled the interaction between the purse-seine and pole-and-line fleets in the Solomon Islands Fishing Zone. The study by Campbell (1994) is illustrative in nature and suggests that, using plausible values for economic and biological parameters, the benefits of a reallocation of the yellowfin tuna stock towards the longline fleet would outweigh the costs to the purse-seine fleet. The study by Campbell and Nicholl (1995) is more complete, incorporating detailed models of the production processes and economics costs of the multi-species purse-seine and longline vessels. In both papers, the results gauge marginal effects measured at existing fleet levels, so they are not likely to be a reliable guide as to what would happen if there was a substantial movement away from the current balance of effort between the two fleets, and, more importantly, compared with a calculation of optimal levels of effort in the fishery.

The study by Hampton et al. (1997) is a bioeconomic model of the purse-seine and pole-and-line fisheries in the Solomon Islands Fishing Zone. While the model has the required level of detail, it deals only with the exploitation of skipjack and yellowfin stocks in a single EEZ. It finds that the rent generated by the two fleets in Solomon Islands could be increased by significantly increasing the level of purse-seine effort above the average level during 1989–91. The model, however, ignores the effect on the region's longline fishery through the impact of additional purse-seining on stocks of adult yellowfin and bigeye tuna.

Research by Bertignac et al. (2000) using a bioeconomic model of the WCPTF and a linear Simplex algorithm estimates the effect of changes in levels and composition of fishing effort in the waters of member countries of the Forum Fisheries Agency on profitability of the fishery in that area. Since the measure of profit by Bertignac et al. is a long-term one that includes profit from all significant tuna fishing activities, it is an appropriate guide to the optimal exploitation of the region's tuna resources. The model accounts for a variety of fishery interactions. One of the most important occurs as a result of purse-seine vessels catching juvenile surface-swimming yellowfin, thereby reducing the number of mature yellowfin found in the mid-water strata and exploited by the longline fleet. Another significant interaction is between the pole-and-line and purse-seine fleets, as they both catch large quantities of skipjack.

Developing the research by Bertignac et al. (2000), a study by Reid et al. (2006) provides an analysis of hypothetical effort reductions using the Western and Central Pacific Ocean Bioeconomic Tuna Model (WCPOBTM). The results of the analysis indicate that if an across-the-board effort reduction were implemented in the WCPTF the total level of rent generated in the WCPTF as a whole is likely to increase, but the net benefits gained are likely to be borne disproportionately by particular fisheries and jurisdictions. The study does not determine optimal effort levels in the fishery. Further developments of the MULTIFAN-CL model by Hampton et al. (2005, 2006a and 2006b) provide detailed analysis of sustainable catch and effort levels for target species and the impacts on stocks of potential management measures. This research provides an essential foundation for the bioeconomic analysis of the region used in this paper.

Bioeconomic model for the WCPTF

Many of the fish resources in the world are characterised by a number of species and fishing grounds, with a group of largely independent sub-fisheries, where the biological and economic interactions are minimal. In these cases, separate bioeconomic models for each species are suitable (Kompas and Che 2006). Even in these cases, however, common species can often be targeted in different regions by different gear types, and potentially from different nations. The economic interdependencies above the water, so to speak, are substantial. In most cases different gear types simultaneously target a range of species in a number of different fishing grounds. To capture this and for notational purposes, aggregate harvest of a fish resource can be expressed by harvest over four dimensions, represented by h_{ijgt}, indicating the harvest of species i by fleet j in area g at time t. The sum of the harvest across each dimension generates the appropriate aggregates.

Biological models

Bioeconomic models must be based on an underlying stock assessment and a stock-recruitment relationship. For the WCPTF, it is assumed that the stock recruitment of each region is relatively independent of the others and follows a Beverton and Holt (1957) model.

Beverton–Holt stock-recruitment relationship. Based on Beverton and Holt (1957), a simple density-dependent mortality model to determine N_t (the number of fish) is given by

$$\frac{dN_t}{dt} = -m_t N_t \tag{1}$$

given that

$$m_t = \mu_1 + \mu_2 N_t \tag{2}$$

where m_t is the rate of natural mortality and μ_1, μ_2 are parameters.

On this basis, Beverton and Holt (1957) established a stock-recruitment relationship model, a solution to Equations 3 and 4, given by

$$R_t = \frac{\mu_3 B_{t-1}}{1 + \mu_4 B_{t-1}} (1 + e^{\xi_1}) \tag{3}$$

where R_t is the recruitment at year t as a result of the spawning stock at the previous time (B_{t-1}); B_0 is the virgin biomass; and μ_3 and μ_4 are parameters. The measure ξ_1 reflects uncertainty or the stochastic behaviour of the spawning stock-recruitment relationship. In its simplest form, the change in the biomass at year t is a sum of fish growth from the surviving stock from the previous year (due to fishing and natural mortality), plus new recruits. Based on Clark (1976) and Bjørndal (1988), the dynamic interactions among recruitment, fish stock, fishing mortality and natural mortality can be expressed by a delay-difference equation of the form

$$B_{t+1} = (B_t - h_t) e^{\delta_t} + R_t \tag{4}$$

where h_t is harvest at time t and

$$\delta_t = g_t - m \tag{5}$$

where g_t is the instantaneous net growth rate and m is the natural mortality rate.

It is clear that there will be relatively more food (or 'environmental capacity') available to a small stock than to a larger one, or that the natural growth rate depends on a biomass density at time t, represented as the ratio between the current biomass over the virgin biomass (Bjørndal 1988). Natural mortality might also be density dependent, for example, if the effectiveness of predation depends on stock size. In a general form, the relationship between the instantaneous net growth rate and biomass density can be expressed as

$$\delta_t = \delta_0 \left(\frac{B_t}{B_0} \right)^{\eta} \tag{6}$$

where δ_0 and η are parameters. At maximum carrying capacity, it can be shown that δ_0 must be negative. In order to maintain the negative relationship between the instantaneous net growth rate and the biomass density, it also can be seen that η must be positive.

The growth length–weight relationship. The growth models presented above should be measured consistently either in terms of fish numbers or fish weight. The fish population of a species consists of a number of different year classes or cohorts, one resulting from each annual spawning and subsequent recruitment. Following Clark (1990), assume that $t=0$ corresponds to the time of recruitment of the first cohort (or the time at which the cohort first becomes available for fishing). At any time t the total biomass of the cohort is

$$B_t = N_t w_t \tag{7}$$

where N_t is the number of fish of the cohort alive at time t and w_t is the average weight of fish at age t. The conversion between fish numbers and fish weight is obtained from the growth in length and length–weight relationship. Based on the von Bertalanffy formula (1938), growth in fish length is given by

$$l_t = l_\infty \left[1 - e^{-k(t-t_0)} \right] \tag{8}$$

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

$$w_t = w_\infty \left[1 - e^{-k(t-t_0)} \right]^{b_i} \tag{9}$$

where w_∞ is maximum weight.

Bioeconomic model

Bioeconomic models combine the relevant biology, given by the stock assessment and the associated stock-recruitment relationship, with a harvest function, total revenue and the total costs of fishing. In a multi-species and multi-fleet model, effort allocation, or the allocation of harvest across vessels and species, must also be specified.

Harvest, revenue, cost and profit functions. The harvest function of a species i by fleet j in area g at time t is given by

$$h_{ijgt} = q^0_{ijg} E^{\alpha_{ijg}}_{ijgt} B^{\beta_{ijg}}_{igt} \tag{10}$$

where i, j and g refer to species i, fleet j and fishing area g for year t. The value q^0_{ijg} is 'catchability'; E_{ijgt} is fishing effort; B_{igt} is biomass (stock); and α_{ijg} and β_{ijg} are the parameters of the harvest function. Given Equation 2, the fish biomass of species i in area g at time t is a function of the total harvest of a species (as a sum of harvest by all fleets), or

$$h_{it} = \sum_{g=1}^{R} \sum_{j=1}^{M} h_{ijgt} = \sum_{g=1}^{R} \sum_{j=1}^{M} q^0_{ijg} E^{\alpha_{ijg}}_{ijgt} B^{\beta_{ijg}}_{igt} \tag{11}$$

Since the fishing effort of fleet *j* is usually measured as total effort for all species in all areas (fishing days or total hooks, and so on), the effort allocation to a species *i* in area *g* is

$$E_{ijgt} = \theta_{jg}\theta_{ij}E_{jt} \tag{12}$$

where θ_{jg} is the regional effort share of fleet *j* to each fishing area, with a constraint that the sum of θ_{jg} over *j* is one. The coefficient θ_{ij} indicates the effective effort allocation among species given the fact that any changes in the effective effort for a species (depending on the stock abundance and the targeted harvest) can influence effective effort for other species (assuming that these 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 revenue (a multiple of harvest and average price) over all species and areas, or

$$TR_{jt} = \sum_{g=1}^{R}\sum_{i=1}^{N} TR_{ijgt} = \sum_{g=1}^{R}\sum_{i=1}^{N} h_{ijgt}\,p_{it} \tag{13}$$

where p_{it} is the price of species *i* at time *t*. Given Equations 11 and 12, the revenue of fleet *j* at time *t* can be expressed as a function of fishing effort allocated to each species and area. Fishing costs (including labour, material, capital and all other costs) are assumed to be a function of fishing effort, so that fishing costs (c_{jit}) for fleet *j* for species *i* in area *g* at time *t* are

$$c_{ijgt} = \gamma_{jg}^{0} + \gamma_{jg}^{1}E_{ijgt} \tag{14}$$

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

Finally, the profit function of fleet *j* at time *t* fishing *i* in area *g* (Π_{ijkt}) is derived from the total revenue and costs of fishing, or

$$\Pi_{ijgt} = p_{it}(q_{ijg}^{0}E_{ijgt}^{\alpha_{ijg}}B_{igt}^{\beta_{ijg}}) - \left(\gamma_{jg}^{0} + \gamma_{jg}^{1}E_{ijgt}\right) \tag{15}$$

Total profit of fleet *j* at year *t* (Π_{it}) is a sum of all species over all areas, or

$$\Pi_{jt} = \sum_{g=1}^{R}\sum_{i=1}^{N}\left[p_{it}(q_{ijg}^{0}E_{ijgt}^{\alpha_{ijg}}B_{igt}^{\beta_{ijg}}) - \left(\gamma_{jgt}^{0} + \gamma_{jgt}^{1}E_{ijgt}\right)\right] \tag{16}$$

and the aggregate profit for the WCPO across all species, all fleets, all fleet groups and all fishing regions at time *t* (Π_t) is the total profit of all fleets over the period *T*, or

$$\Pi = \sum_{t=1}^{T}\sum_{j=1}^{M}\sum_{g=1}^{R}\sum_{i=1}^{N}\begin{bmatrix} p_{it}(q_{ijg}^{0}(\theta_{ig}\theta_{ij}E_{jt})^{\alpha_{ijg}}B_{igt}^{\beta_{ijg}}) \\ -\left(\gamma_{jg}^{0} + \gamma_{jg}^{1}(\theta_{ig}\theta_{ij}E_{jt})\right) \end{bmatrix} \tag{17}$$

where E_{ijgt} is obtained from E_{jt} as indicated in Equation 12.

Fish prices in a demand and supply framework. Following Reid et al. (2003), fish prices received by suppliers are a function of initial prices, the initial and new quantity supplied and the elasticity of demand, or

$$p_{it} = p_{i0} - p_{i0}\left(\frac{h_{it} - h_{i0}}{h_{i0}}\right)/\,\varepsilon_i \tag{18}$$

where p_{i0} is the initial price when the volume of harvest of species *i* is h_{i0} (or the initial supply) at a baseline; ε_i is the elasticity of demand for catch for species *i*; and h_{it} is total harvest of species *i* for all fleets and all fishing grounds at time *t* given by Equation 11.

Objective function. The optimisation problem is to maximise aggregate profit over a period of time *T* through choice of the effort of each fleet by nation for each species in each fishing ground. In other words, the problem is to maximise the objective function given by

$$\max_{E_{jt},\theta_{jg},\theta_{ij}} \Pi_t = \sum_{t=1}^{T}\frac{1}{(1+r)^t}\sum_{j=1}^{M}\sum_{g=1}^{R}\sum_{i=1}^{N}\begin{bmatrix} p_{it}(q_{ijg}^{0}(\theta_{ig}\theta_{ij}E_{jt})^{\alpha_{ijg}}B_{igt}^{\beta_{ijg}}) \\ -\left(\gamma_{jg}^{0} + \gamma_{jg}^{1}(\theta_{ig}\theta_{ij}E_{jt})\right) \end{bmatrix} \tag{19}$$

subject to the underlying biology or stock-recruitment relationship, where r is the discount rate. A solution to Equation 19 also requires that virgin biomass at time 0 for each species is known.

Bioeconomic equilibrium

Given the optimal total allowable catch (TAC) or total allowable effort (TAE) for each species in each fishing ground, equilibrium solutions require that the marginal benefit of fishing across species, fleets and fleet groups in a region be equalised (Kompas and Che 2006). In more precise terms, the marginal benefit of fleet j for species i in region g at time t (MB_{ijkgt}) is obtained by finding the first variation of Equation 16 or

$$MB_{ijgt} = \frac{\partial \Pi_{ijgt}}{\partial E_{ijgt}} = p_{it}\left(\alpha_{ijg} q^{0}_{ijg} \left(\theta_{ij}\theta_{jg}\right)^{\alpha_{ijg}} E_{jt}^{\left(\alpha_{ijg}-1\right)} B_{igt}^{\beta_{ijg}} \right) - \gamma^{1}_{jgt} \qquad (20)$$

using effort as the index; and, if α_{ijg} is less than one, it follows that marginal benefit (MB_{ijgt}) decreases with the effort E_{jt}. The equilibrium allocation of harvest thus results from equating the marginal benefit of fishing across each i, j and g.

The WCPTF and model context

Total fish landed in the WCPTF has been increasing steadily since 1950 at a rate of 5 per cent a year. The dominant species are albacore, yellowfin, bigeye and skipjack, which contributed about 2 million metric tonnes a year in the past 10 years. Although skipjack accounts for 65 per cent of total catch, this species is valued at a lower price than other species supplied to the premium sashimi market. Yellowfin tuna contributes 22 per cent of total catch and is divided into two groups, one to the canning market at a lower price and one to the premium sashimi market at a higher price. Bigeye shares are only 6 per cent of the total catch in the region, but supply mostly the premium sashimi market. Along with harvest, fishing effort in the WCPTF has been growing rapidly. For the purse-seine fisheries during 1970–2000, total boat-days have increased on average at a rate of 10 per cent a year. In 2004, total fishing effort for the purse-seine fleet was more than 70,000 boat-days. For the longline fisheries, total hooks increased from more than 100 million in the 1950s to 700 million hooks in 2004 (SPC 2006).

Fishing regions

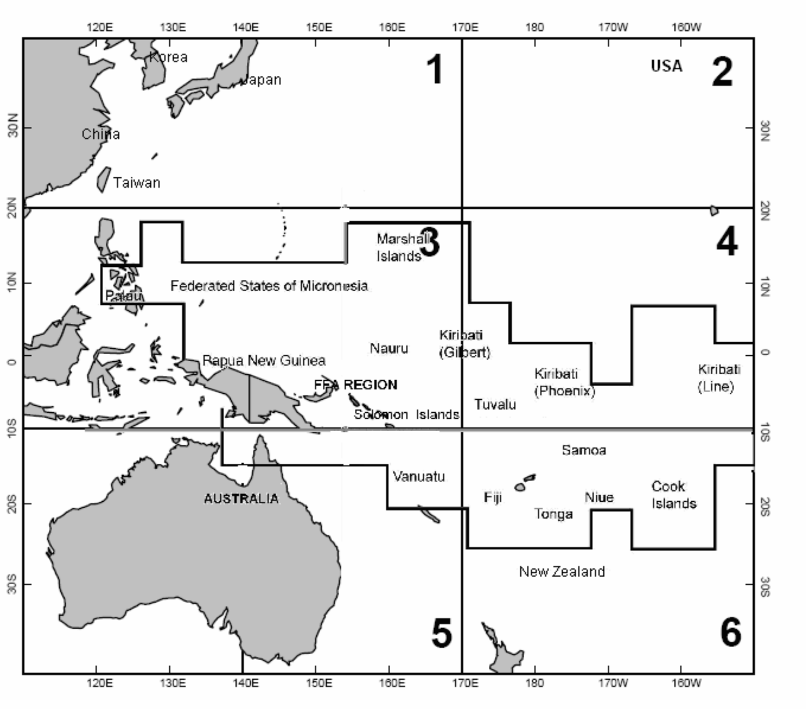
The WCPTF is defined by the coordinates 40°N to 40°S and 100°E to 150°W. The different spatial stratifications are used for each species, depending on the stock-recruitment characteristics. Based on Hampton et al. (2005), the spatial stratification of the WCPTF includes six fishing areas (see Figure 1).

About 200 high islands, 2,500 low islands and 22 countries 'reside' in this fishing area. A brief summary of harvest by species and regions is indicated in Table 1. Based on SPC (2006), it is estimated that about 90, 80 and 87 per cent of yellowfin, bigeye and skipjack, respectively, are landed in regions three and four. The bioeconomic model thus concentrates on these species and regions.

Fishing gear

The four major gear methods used in the WCPTF are purse-seine, pole-and-line, frozen tuna and fresh tuna longline, of which purse-seine and longline are the most important. Purse-seine contributes more than 75 per cent of the total catch of yellowfin tuna, which supplies mainly the canning market. The purse-seine fishery developed rapidly in the late 1970s and 1980s in response to an improved technical capability to fish the deeper thermocline found in the WCPTF,

Figure 1 **Spatial stratification of the Western and Central Pacific tuna fisheries**



Sources: Hampton, J., Langley, A., Harley, S., Kleiber, P., Takeuchi, Y. and Ichinokawa, M., 2005. *Estimates of sustainable catch and effort levels for target species and the impacts on stocks of potential management measures*, Working Paper WCPFC-SC1 SA WP-0, First Meeting of the Scientific Committee of the Western and Central Pacific Fisheries Commission, WCPFC-SC1, August 2005, Noumea, New Caledonia. Secretariat of the Pacific Community, 2006. *WCPO Yearbook Database*. Available from http://www.spc.org.nc/oceanfish/Html/SCTB/SCTB16/index.htm

poor fishing conditions in the eastern Pacific Ocean, and the emergence of the Korean, Taiwanese and Japanese purse-seine fleets. In addition, in the early 1990s there was a shift of the US purse-seine fishing effort from the eastern Pacific to the WCPTF in response to consumer boycotts of tuna caught with dolphin bycatch—a problem encountered only in the eastern Pacific Ocean. The introduction of the *1990 Dolphin Protection Consumer Information Act* in the United States prompted canneries to require that purse-seine vessels fishing in the eastern tropical Pacific provide certification that their tuna catches were not taken with dolphins (Bertignac et al. 2000).

The longline fishery continues to account for about 10 to 12 per cent of the total WCPTF catch (Lawson 2004), but rivals the much larger purse-seine catch in landed value. According to Bertignac et al. (2000), the subsequent decline of the pole-and-line fleet is attributable mainly to the emergence of the purse-seine fleet, which has been more efficient at supplying canning-grade tuna. The longline fleet, which supplies predominantly the Japanese sashimi market, has declined in terms of its percentage of the total catch over time. Because sashimi fetches prices much in excess of those paid for canning-grade tuna, however, revenues are almost as high as those of the purse-seine fishery. Longline catches peaked in 1980 (170,000 metric tonnes), then went through a period of moderate decline, falling to a low of 85,000 metric tonnes in 1989. From the early to mid 1990s, the catch rose to 180,000 metric tonnes a year in 2000 (SPC 2006). The increase in vessel numbers was due mainly to the improvement in airfreighting logistics for fresh tuna, which prompted a large influx of fresh tuna longline vessels.

Bigeye tuna landed by longline is supplied to the premium (sashimi) market at high prices (four times higher than the purse-seine fish price). Longline also provides the most important harvest for albacore (mostly in regions five and six in Figure 1). It provides the longest time series of catch estimates for the WCPTF, with estimates available since the early 1950s (Lawson 2004). In 2003, there were 5,000 longline vessels active with two main types of operation, the frozen longline and the fresh longline fisheries.

Table 1 **Average annual catch by ground, gear and species, 1990–2000** (‘000 metric tonnes)

	Region 1 and 2	Region 3	Region 4	Region 5	Region 6	Total
Yellowfin tuna						
Longline	1.24	28.21	34.65	4.07	11.80	79.97
Purse-seine	4.06	117.38	79.38	0.79	0.47	202.08
Pole-and-line	3.25	8.28	0.21	0.02	0.18	11.94
Total	8.55	153.87	114.24	4.88	12.45	293.99
Bigeye tuna						
Longline	7.23	14.88	70.11	1.36	17.23	110.81
Purse-seine	0.87	13.40	8.38	0.08	0.06	22.8
Total	8.10	28.28	78.49	1.44	17.29	133.61
Skipjack						
Pole-and-line	72.21	131.57	18.87	1.20	2.95	226.8
Purse-seine	38.90	423.4	302.94	3.72	7.42	776.37
Total	111.11	554.97	321.81	4.92	10.37	1,003.17
Albacore						
Longline	12.57	2.2	6.23	4.44	30.65	56.09
Drift-net	n.a.	n.a.	n.a.	10.29	21.35	31.64
Total	12.57	2.2	6.23	14.73	52.00	87.73
Others						
Purse-seine	10.76	0.64	0.14	1.37	0.01	12.91
Pole-and- line	1.19	0.28	0.01	0.29	0.04	1.81
Total	11.95	0.92	0.15	1.66	0.05	14.72

Note: Drift-net data is estimated from the only available statistics for 1980–90.
Source: Compiled from Secretariat of the Pacific Community, 2006. *WCPO Yearbook Database*. Available from http://www.spc.org.nc/oceanfish/Html/SCTB/SCTB16/index.htm

Optimal effort in the Western and Central Pacific Ocean tuna fishery

The bioeconomic model is applied to the purse-seine, frozen longline and fresh longline fisheries, which contributed more than 73 per cent of the total catch in the WCPTF, on average, during the past four years (SPC 2006), with 12 different fleets (the United States, Japan, Korea, and so on, as in Reid et al. 2006), aggregated by effort units, and three main species: yellowfin tuna, bigeye tuna and skipjack.

Biological analysis

The biological structure and the parameters used for the model are based on Hampton et al. (2006a and 2006b) and Langley et al. (2005). Quarterly cohort structures are developed in the model, which allow the age structure of the population at a time in the investigated period and the effects of harvest on stock to be determined. The initial size of the cohorts is determined by present recruitment, after which time cohort attrition occurs due to natural and fishing mortality. The population is partitioned into 28, 40 and 16 quarters for yellowfin tuna, bigeye tuna and skipjack respectively. The final age class is a sum of all fish of that age and older. 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 the Beverton–Holt stock-recruitment relationship. This is a discrete approximation to continuous recruitment with the Beverton–Holt coefficients (μ_3 and μ_4) by species and regions, with estimates based on the biomass studies of Hampton et al. (2006a and 2006b) and Langley et al. (2005).

Standard assumptions made concerning age and growth are

- the lengths at age are normally distributed for each age class
- the mean lengths at age follow a von Bertalanffy growth curve
- the standard deviations of length for each age class are a log-linear function of the mean lengths at age
- the distribution of weight at age is a deterministic function of the length at age and a specified weight–length relationship.

Natural mortality (M) is assumed to be age-specific, invariant over time and region and continuous through the time steps. Further details are found in Hampton et al. (2006a and 2006b) and Langley et al. (2005).

The current biomass, the virgin biomass and the current rates of exploitation of each species are estimated as the average for 2001–04 from Hampton et al. (2006a and 2006b) and Langley et al. (2005). For regional analysis, the region classification for yellowfin tuna and bigeye tuna follows Hampton et al. (2005) (as indicated in Figure 1). For skipjack, however, the WCPTF is divided into six fishing regions (Langley et al. 2005). For simplification, for the skipjack fishery we use one aggregated region for regions five and six, because these regions closely match the area covering regions three and four for yellowfin and bigeye tuna in the WCPTF.

Harvest functions

Based on the harvest functions given by Equation 10, the econometric specification for vessel type j for species i is given by

$$\ln h_{ijg} = \alpha^0_{ijg} + \alpha_{ijg} \ln E_{jg} + \beta_{ijg} \ln B_{ig} \qquad (21)$$

where h, E and B is harvest, fishing effort (boat-days for purse-seine and number of hooks for longline) and fish stock respectively, and α^0_{ijg}, α_{ijg} and β_{ijg} are parameters to be estimated. Although Equation 21 is indicated at fleet level, given the available data, estimates are obtained only for purse-seine and longline fleets as a whole.

The estimated results of harvest functions of purse-seine fleets for yellowfin, bigeye and skipjack are given in Tables 2 and 3. The estimated results for harvest functions for the longline fisheries for yellowfin and bigeye are reported in Table 4.

Since only a short time series (1990–2003) is available, an aggregated regression is used for regions three and four, with a regional dummy variable. The value of catchability for each fleet is computed directly by using Equation 10 for average values during 2000–04, or

$$q^{0}_{ijg} = h_{(ijg,2000s)} / E^{\alpha_{ijg}}_{(ijg,2000s)} B^{\beta_{ijg}}_{(ijg,2000s)} \quad (22)$$

where h, E and B is the average harvest, fishing effort and fish stock respectively during 2000–04. The parameters of α^{0}_{ijg}, α_{ijg} and β_{ijg} at 2004 are the estimated parameters obtained from regressions of Equation 21. Data for the estimates are provided from the SPC (2006) at each separate fleet level.

Effort and harvest analysis

The model includes the purse-seine, frozen longline and fresh longline fisheries, which contributed more than 73 per cent of the total catch in the WCPTF during 2000–04 (SPC 2006). Twelve fleets are included in the model: five purse-seine fleets (United States, Japan, Korea, Taiwan, and Pacific island and others), three frozen longline fleets (Japan,

Table 2 **Harvest function of purse-seine fleet in region 3, 1972–2002**

Regressor	Yellowfin tuna		Bigeye tuna		Skipjack	
	Coeff.	T ratio	Coeff.	T ratio	Coeff.	T ratio
Constant	-2.00	0.55	-2.41*	1.1	-0.21	0.5
		(2.18)		(2.20)		(0.41)
Effort (day)	0.80***	17.49	0.86***	10.33	1.09***	17.33
		(0.05)		(0.08)		(0.06)
Stock (tonnes)	0.52*	1.21	0.44	0.97	0.15*	1.5
		(0.42)		(0.40)		(0.10)
Number of obs	31		25		21	
R-squared	0.96		0.96		0.96	
Adj. R-squared	0.96		0.96		0.96	
F Stat.	0.00		0.00		0.00	
Akaike criterion	25.52		20.46		25.05	
Schwarz Bayes criterion	23.37		18.63		23.42	
DW test	1.25		1.21		1.17	

All estimates passed the serial correlation test for orders 1–3.
* significance at the 0.10 level
** significance at the 0.05 level
*** significance at the 0.01 level
Notes: The data are not available for some earlier years for bigeye and skipjack. Numbers in parentheses are asymptotic standard errors.
Source: Authors' calculations.

Korea and Taiwan) and four fresh longline fleets (Japan, China, Taiwan, and Pacific island and others). At this stage, the bioeconomic model focuses on regions three and four for tuna, where 90 per cent, 80 per cent and 87 per cent of total catch of yellowfin, bigeye and skipjack, respectively, are landed by the purse-seine and longline fisheries (SPC 2006).

Based on Reid et al. (2006), the spatial distribution of effort of each fleet in each year is assumed to be constant at the recent average (computed from Hampton et al. 2005). Therefore, in the model, the proportion of total fleet effort allocated to each region (θ_{jg}) in Equation 13 is given, although the total level of effort might be varied. The initial number of purse-seine boats by region is taken from Hampton et al. (2005). Effort by fleet is computed based on Hampton et al. (2005), SPC (2005) and Miyabe et al. (2004) (for Japanese purse-seine). The average number of fishing days per annum of each purse-seine fleet is 221, 175, 231, 220 and 200 for the United States, Japan, Korea, Taiwan and the Pacific island countries respectively (based on Reid et al. 2003; Miyabe et al. 2004; and SPC 2006).

The initial number of frozen and fresh longline boats is taken from SPC (2005). The average number of hooks per boat for frozen longline is from SPC (2005), Yang et al. (2004), Overseas Fisheries Development Council of the Republic of China and Fisheries Agency, Council of Agriculture, Republic of China (2004) and Miyabe et al.

Table 3 **Harvest function of purse-seine fleet in region 4, 1983–2002**

Regressor	Yellowfin tuna		Bigeye tuna		Skipjack	
	Coeff.	T ratio	Coeff.	T ratio	Coeff.	T ratio
Constant	-3.88*	1.1 (3.83)	-23.22***	3.89 (5.95)	-0.78	0.8
Effort (day)	0.90***	18.21 (0.07)	1.20***	13.41 (0.1)	1.10***	17.28
Stock (tonnes)	0.60	0.90 (0.60)	4.07***	3.66 (1.11)	0.21	0.8
Number of obs	20		20		20	
R-squared	0.95		0.91		0.96	
Adj. R-squared	0.95		0.90		0.96	
F Stat.	0.00		0.00		0.00	
Akaike criterion	7.52		0.91		11.23	
Schwarz Bayes criterion	6.02		0.6		9.73	
DW test	2.31		1.69		1.78	

All estimates passed the serial correlation test for orders 1–3.
* significance at the 0.10 level
** significance at the 0.05 level
*** significance at the 0.01 level
Notes: The data are not available for some earlier years for bigeye and skipjack. Numbers in parentheses are asymptotic standard errors.
Source: Authors' calculations.

Table 4 **Harvest function of longline fleet for regions 3 and 4, 1990–2003**

Regressor	Yellowfin tuna		Bigeye tuna	
	Coeff.	T ratio	Coeff.	T ratio
Constant	3.37 (2.99)	1.12	-4.10 (3.68)	1.11
Effort (hooks)	0.30* (0.21)	1.40	0.74*** (0.20)	3.56
Stock (tonnes)	0.23 (0.23)	1.00	0.96*** (0.39)	2.45
Regional dummy (Region 3=1)	0.024 (0.08)	0.29	-1.00*** (0.18)	5.58
Number of obs	28			
R-squared	0.28			
Adj. R-squared	0.19			
F Stat.	3.04			
Akaike criterion	28.84			
Schwarz Bayes criterion	26.17			
DW test	1.60			

All estimates passed a heteroscedasticity test for orders 1–3.
* significance at the 0.10 level
** significance at the 0.05 level
*** significance at the 0.01 level
Notes: The data are not available for some earlier years for bigeye and skipjack. Numbers in parentheses are asymptotic standard errors.
Source: Authors' calculations.

(2004). The average number of hooks per boat for frozen longline is obtained from SPC (2005). The initial annual average harvest by each fleet group in the model is computed from the WCPTF database (SPC 2006) and the *Tuna Fishery Yearbook* (SPC 2005). Albacore is the important species for some fisheries, such as Japanese purse-seine, Japanese frozen longline, Taiwanese frozen longline, Pacific island country frozen longline, etc. Therefore, the revenue of these fisheries is adjusted by the income sources from albacore.

Fish prices, price elasticity and costs

Fish prices by species and fleets are indicated in Table 5. These prices are computed from Reid et al. (2006) with the 2004 Consumption Price Index adjustment (based on CPI for US dollars; USDB 2006). Further details can be found in Pacific Island Centre (PIC 2006).

Based on Reid et al. (2003), the demand elasticity (ε) for raw tuna for the light meat canned tuna market is estimated as 1.9, implying that a 1 per cent rise in the quantity of canning tuna supplied by the WCPTF will cause a 0.52 per cent fall in price. Based on

Reid et al. (2003), the demand elasticity (ε) for raw tuna for the fresh and frozen light meat canned tuna market for the Forum Fisheries Agency (FFA) is estimated as 9.97. This figure comes from the fact that the FFA region supplies only 11 per cent of the world's fresh and frozen tuna market. Based on the statistics of the Food and Agriculture Organization (FAO 2005), it is estimated that the share of the WCPTF in total tuna supplies for the world fresh and frozen tuna market is about 50 per cent. Therefore, the demand elasticity (ε) for raw tuna for the fresh and frozen light meat canned tuna market for the Forum Fisheries Agency is adjusted at about 2, implying that a 1 per cent rise in the quantity of canning tuna supplied by the WCPTF will cause a 0.5 per cent fall in price. Fishing costs by fleet group are obtained from Reid et al. (2003 and 2006) with the 2004 price adjustments based on CPI for US dollars (USDB 2006) (see Table 5). Fishing costs are provided by cost per effort (US$/boat-day for purse-seine and US$/hooks for longline).

The optimisation problem

Equation 19 provides the generic optimisation problem in order to maximise aggregate profit over a period of time T through choice of the effort for each fleet for each species in each fishing region as indicated. Given the specific conditions of the WCPTF, the problem is simplified in the following ways. First, it is assumed that effort is 'equalised' for each fleet (from the different nations) using the same fishing method. Therefore, the optimal effort will be solved in terms of three gear types only: purse-seine, frozen longline and fresh

Table 5 **Fish prices by species and fleets** (US$/tonne, 2004 prices)

Fleet	Cost parameter	Skipjack	Yellowfin	Bigeye
Purse-seine				
United States	23,485 per day	859	1,204	1,204
Japan	30,164 per day	1,106	1,583	1,583
Korea	22,603 per day	781	1,135	1,135
Taiwan	16,849 per day	781	1,135	1,135
Pacific island countries and others	18,240 per day	781	1,135	1,135
Frozen tuna longline				
Japan	3.3 per hook		4,567	8,039
Korea	2.5 per hook		4,098	7,254
Taiwan	1.1 per hook		4,098	7,254
Fresh tuna longline				
Japan	2.0 per hook		4,539	11,381
China	1.4 per hook		5,606	5,491
Taiwan	1.6 per hook		5,767	4,985
Pacific island countries and others	1.6 per hook		4,398	5,960

Sources: Reid, C., Vakurepe, R. and Campbell, H., 2003. *Tuna Prices and Fishing Costs for Bioeconomic Modelling of the Western and Central Pacific Tuna Fisheries*, ACIAR Project No. ASEM/2001/036. Reid, C., Bertignac, M. and Hampton, J., 2006. *Further development of, and analysis using, the Western and Central Pacific Ocean Bioeconomic Tuna Model (WCPOBTM)*, Technical Paper No. 2, ACIAR Project No. ASEM/2001/036. United States Department of Labor (USDB), 2006. Available from http://www.bls.gov/news.release/cpi.nr0.htm longline (instead of 12 fleets belonging to these gear types). Second, as indicated above, the spatial distribution of effort of each fleet in each year (θ_{jg}) is given and computed as the average for 2000–03 from Hampton et al. (2005), although the value for effective allocation (θ_{ij}) can vary over time.

Results

The baseline total profit for purse-seine, frozen longline and fresh longline is $84 million, US$41 million and US$30 million respectively. The discount rate is taken as 5 per cent. Table 6 provides the final results, where the effort for base year 2004 is 100 per cent. In the first five years of the dynamic path, optimal effort for purse-seine, frozen longline and fresh longline should be reduced to 64, 88 and 81 per cent of baseline values respectively. At (near) steady state, effort for purse-seine, frozen longline and fresh longline is 68, 92 and 83 per cent, respectively, of baseline values. Maximising economic profits, therefore, requires substantial reductions in effort levels in the WCPTF, providing an analytical case for the call for effort reduction in Parris and Grafton (2006). Profit calculations indicate that obtaining optimal, compared with current, effort levels would increase profits in the fishery by roughly 30 per cent a year.

Table 6 also indicates the optimal allocation of effort across species. Current effort in the fishery is indexed at 100 units per species. Thus, for purse-seine, in steady

Table 6 **Optimal results** (discount rate = 0.05, T = 50)

Fleet	Optimal effort level (per cent)	Optimal effort allocation (per cent)		
	Base year=100	Base current effort =100 per species Total effort (E_t) =300 (3 species) Total effort (E_t) =200 (2 species)		
		Yellowfin	Bigeye	Skipjack
Purse-seine				
In the first 5 years	64	93.3	71.4	135.3
Steady state	68	98.0	88.3	113.7
Frozen long-line				
In the first 5 years	88	103.0	97.0	
Steady state	92	100.0	100.0	
Fresh long-line				
In the first 5 years	81	114.0	86.0	
Steady state	83	116.0	84.0	
Biological status for species				
Ratio	Denotation	Yellowfin	Bigeye	Skipjack
Biomass at steady state to biomass at MSY	B^*/B_{MSY}	1.33	1.81	1.90

Source: Authors' calculations.

state, effort for yellowfin should decrease slightly, compared with current levels, and more so for bigeye. For skipjack, effort levels are 113.7, compared with the current base of 100. In frozen longline, effort levels are reduced overall, but effort allocation is the same in steady state as in current levels. For fresh longline, effort should increase for yellowfin and fall for bigeye, compared with current levels.

Finally, Table 6 indicates the ratio of optimal stock to maximise profits (MEY) to stock at maximum sustainable yield (MSY). Measures of MSY are part of model outcomes and are consistent with the stock analysis given by Hampton et al. (2006a and 2006b) and Langley et al. (2005) for regions three and four, taken separately. Optimal results show the need for stocks substantially larger than stocks at MSY.

Concluding remarks

This paper has developed a bioeconomic model of the WCPTF for three main species. Optimal results indicate that in order to maximise economic profits in the WCPTF, there should be significant reductions in effort from 2004 values, and a change in the effort allocation across species. The largest cuts in effort occur in the purse-seine fishery, with effort reductions amounting to 68 per cent of effort levels in 2004 over a 50-year planning horizon. Effort is also optimally reduced in the frozen and fresh longline fishery. Reductions in effort allow stock recovery and increased profits through reductions in per unit costs of fishing. The increase in profits from this change is substantial, in the order of 30 per cent per annum in perpetuity. The move would also potentially allow for increased licence fees by Pacific island states.

What remains to be discovered and implanted is an institutional mechanism that will allow all WCPTF participants to manage the fishery at optimal effort levels. This can be a considerable challenge, especially since full optimality would also imply a reallocation of effort across existing nations in the WCPTF. The cost of not resolving this problem is a substantial loss in profits. In addition, optimal effort levels indicate stock values substantially larger than stock at MSY. Pursuing optimal results would thus also help ensure sustainability of tuna in the Pacific Ocean.

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