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Rent-Maximization versus Competition in the Western and Central Pacific Tuna Fishery

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Abstract

Where a fish stock straddles or migrates between country A's exclusive economic zone (EEZ) and country B's EEZ, or the high seas, vesting ownership rights in the stock with A does not ensure efficient harvesting of the stock. This problem arises in the case of migratory tuna stocks in the Western and Central Pacific Ocean (WCPO). Four species of tuna reside for only part of the year in the EEZs of coastal states, many of which are Pacific Island Countries (PICs). Most of the harvesting of the stocks is carried out by distant water fishing nations such as the USA, Japan, Taiwan, China and Korea.

Problems arise for achieving efficiency and equity in the harvesting of the stocks by disparate countries. The problems are made more difficult by changes in the harvesting levels of one fleet affecting the rents of another fleet through changes in the age distribution of stock. These types of problem are under review by the Western and Central Pacific Fisheries Commission, formed in 2005. Results from an age-structured steady-state bioeconomic model are used to show: the changes in fleet rents and catches of tuna if all fleets form a cooperative grand coalition to deploy fishing effort to maximize rents over the WCPO; the likely non-stability of the grand coalition; and the inferior Nash Equilibrium outcomes if all fleets fish non-cooperatively to maximize their own rents.

Keywords: Bioeconomic modelling, Game theory, Optimisation, Migratory tuna

INTRODUCTION

The tuna fishery in the western and central Pacific is conducted by fleets from many different nations. Traditionally fishing in this area was mainly done by the Japanese, who fished with longline or pole and line. Over time new nations, especially Taiwan and Korea, emerged in the longline fishery. Furthermore, from the 1970s on, fishing by purse seine increased rapidly. Purse seining is carried out by a variety of nations: the United States, Indonesia, the Philippines, and the Pacific island nations, in addition to those involved in longlining.

When fishing fleets from different nations compete for a common fish stock, the result is likely to be overexploitation, both in the biological and the economic sense. The life span of tuna is several years, in which case biological overexploitation means that most fish are caught too young, before they have reached the age of maximum age group biomass. In addition, recruitment of young fish may be adversely affected by reducing the spawning stock too far, but little is known about the relationship between the spawning stock biomass and recruitment to the stock. In economic terms overexploitation means that there are too many fishermen and boats, raising the fishing costs to an unnecessarily high level.

An additional aspect of the possible economic overexploitation of the tuna stocks in the western and central Pacific is the effect of purse seining on the longline fishery. Purse seine fishing is carried out primarily for skipjack tuna, but also for yellowfin, and some bigeye tuna also get entangled in the seines. The catching of yellowfin and bigeye tuna has a detrimental effect on the longline fishery, because the purse seiners primarily take young tuna which would otherwise have grown older and become available for the longline fishery. The question therefore arises whether reducing the purse seine fishery for bigeye and yellowfin would be advisable. Do these fish represent a higher value if left for the longline fishery, or had they better be taken by the purse seine fishery?

In this paper we shall look at the interaction between the purse seine fishery and the longline fishery. Would it make sense, from an overall point of view, to reduce the former for the benefit of the latter? This is a part of the larger issue of what rate and pattern of exploitation would maximize the economic rent in the fishery. Which fleet should participate in the fishery and on what scale? Given that such a solution would most likely entail some fleets fishing less than presently or not at all, could such a solution be implemented by some kind of rent sharing? And if not, or if a rent-maximizing solution is unlikely to be implemented for other reasons, what kind of outcome can we expect when all national fleets compete against each other? These are the types of question being raised by the recently established Western and Central Pacific Fisheries Commission (see Kennedy, 2006), and that we shall try to answer in this paper.

We shall consider three stocks that are likely to be, to a greater or lesser degree, mixed in the fishing areas and hence fished to some extent indiscriminately by the fishing fleets. These are bigeye, yellowfin and skipjack. Both are found mainly in the tropical areas between 10 degrees north and south of the equator. Albacore tuna, also fished in the western and central Pacific, is mainly found further south and therefore to a lesser extent fished indiscriminately together with the other three.

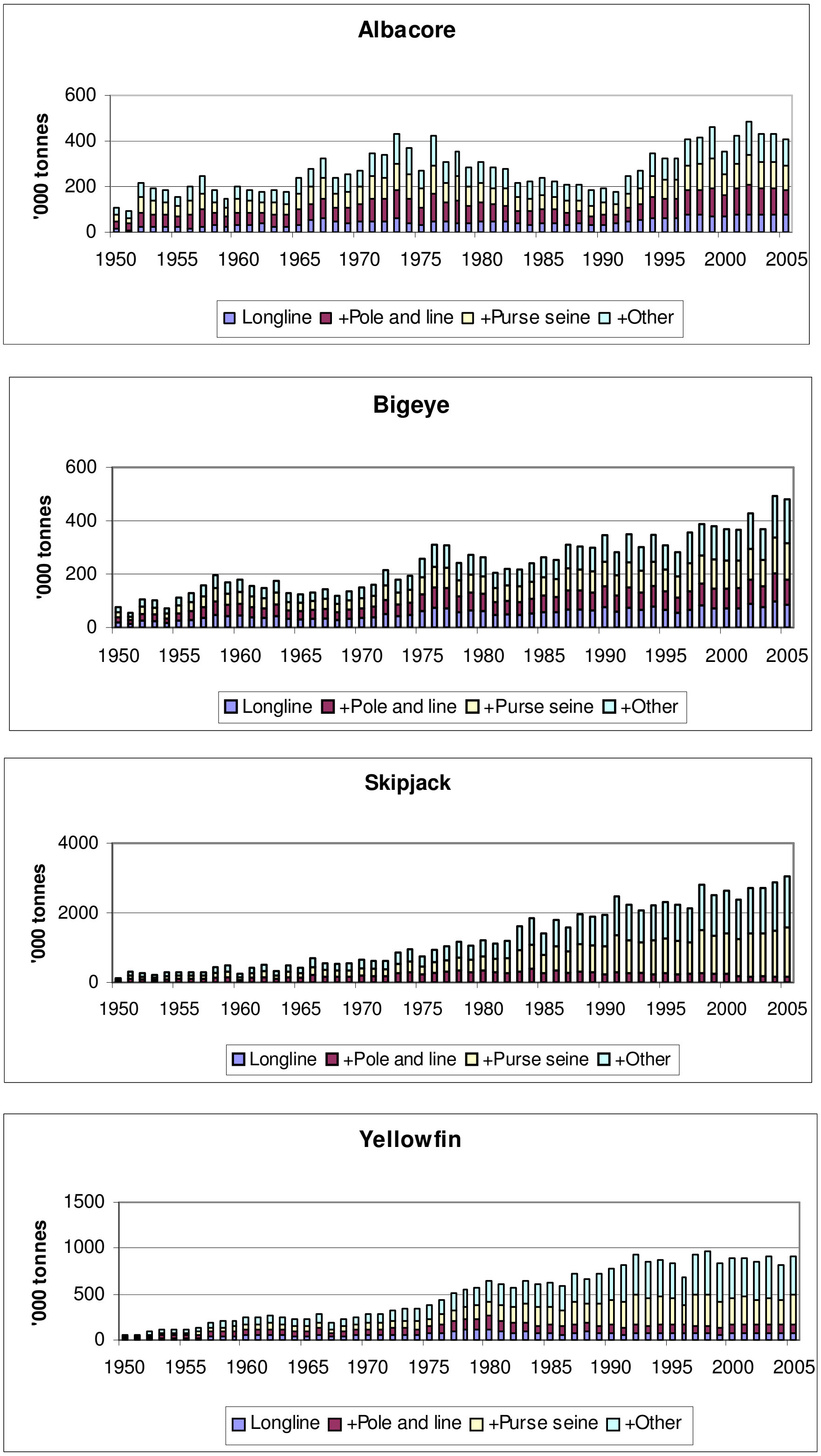


Figure 1: Catches of tuna in the Western and central Pacific (source: WCPFC Tuna Fisheries Yearbook. Secretariat of the Pacific Community).

The question of maximizing rents in the western and central Pacific tuna fishery has been analysed before. Bertignac and others (2001) used a detailed age structured model with a number of different fleets to look into the effects of changing the size of different fleets. They calculated the rent gains versus losses from changing fishing effort for the different fleets and the interaction between different fleets for the different stocks involved. The emphasis here is somewhat different. We look not just at the rent-maximizing solution, but also at whether under ideal circumstances a grand, rent-maximizing coalition is likely to be stable, and what would be the outcome of competition among the fleets of the various nations participating in the fishery. For this reason a simpler model of the tuna stocks than the one used by Bertignac et al. (2001), which is highly disaggregated spatially and allows for average rates of advection and diffusion of stock between the 5 degree squares making up the western and central Pacific region. When possible data from the disaggregated model are used in the much simpler highly aggregated model, but some of the model changes lead to requirements for different parameter estimates. The way in which some parameters were tuned to obtain good model fits between modelled and actual catches is described below.

THE MODEL

The model employed is a yield per recruit model. Each age interval is one quarter. Growth, natural mortality and gear selectivity parameters were taken from the WCPOBTM-model (Reid et al., 2006).

Two fisheries are considered, the purse seine fishery and the longline fishery. These are the dominating types of gear nowadays, while earlier pole and line in particular was important. The pole and line fishery is included with the purse seine fishery, as the selectivity patterns for both gear types are identical for bigeye and yellowfin tuna. In addition, there are other fisheries, of which domestic Indonesian and Philippine fisheries are important components. We will not consider these fisheries any further, except including them as a residual fishery with a constant fishing mortality.

Figure 1 shows the tuna catches in the western and central Pacific since 1950. Except for albacore, the total catches have increased in an almost linear fashion. Since the 1990s most of the skipjack has been taken by purse seines. This is true to a lesser extent for yellowfin, of which substantial catches are taken by longlines. Most of the bigeye is taken by longlines, but there is a non-negligible catch by purse seines, which is on the rise. The use of pole and line is in decline.

For modelling purposes, a steady state age-structured stock system is simulated as follows. Stock in each age category is reduced over each quarterly fishing season by natural mortality and fishing mortality set by harvesting effort. Stock in the first age category is replenished in each quarter at a constant rate of recruitment. This is a simplification to the extent that recruitment is here not a function of the adult biomass of the stock. As numbers decline in older age categories, the effect on biomass is to some degree offset by the increasing average unit weight of the stock.

For each stock species *s*, the population $x_{i,s}$ in each quarterly age category *i* from 1 to *I* is:

$$
\begin{aligned}
&x_{1,s} = x_{r,s} \\
&x_{i,s} = x_{i-1,s} e^{-f_{i,s}-m_{i,s}} \qquad\qquad i = 2,..., I_s - 1;\; s = 1,2,3 \\
&x_{I,s} = (x_{I-1,s} + x_{I,s}) e^{-f_{i,s}-m_{i,s}}
\end{aligned}
\tag{1}
$$

with $f_{i.s} = q_i s_{i,s} E_s$, and where $x_{r,s}$ is recruitment numbers into the first age category, $f_{i,s}$ and $m_{i,s}$ are the quarterly instantaneous rates of fishing (aggregated across fleets) and natural mortality respectively, q_s and $s_{i,s}$ are availability and selectivity coefficients respectively, and e_s is quarterly fishing effort.

Catch for species *s* accumulates from each age category over the season, dependent on natural and fishing mortality, and unit weight, as follows:

$$
\begin{aligned}
c_s &= \sum_{i}^{I,s} f_{i,s} x_{i,s} w_{i,s} \int_0^1 e^{(-f_{i,s}-m_{i,s})t} dt \\
&= \sum_{i}^{I,s} x_{i,s} w_{i,s} (e^{-f_{i,s}-m_{i,s}} - 1) f_{i,s} / (f_{i,s} + m_{i,s})
\end{aligned}
\tag{2}
$$

where $w_{i,s}$ is the average unit catch weight of fish in the *i*-th age category.

The model is not dynamic in that the decision variables $f_{i,s}$ remain the same for all quarterly time periods. However, this enables the impact of changes in $f_{i,s}$ on steady state stocks, catches and rents to be readily determined by iterating to the steady state.

Tuning with respect to a vector of parameters $\boldsymbol{p}$ to be estimated was conducted by solving the following problem:

$$
\min_{\boldsymbol{p}} \sum_{s=1}^{3} (\hat{c}_s - c_{s,2005})^2 \tag{3}
$$

With given age-specific weight, natural mortality and selectivity, it is possible to tune the model by finding the fishing mortalities that reproduce the catches taken by the three types of gear in some reference year. This was done for the catches taken in 2005, but the resulting fishing mortalities produced much too low survival rates for all three stocks (less than one percent for all stocks at what the WCPOBTM model considers the terminal age). This implies a severe overexploitation of all three stocks, which in turn implies enormous and in all probability unrealistic gains from reducing fishing effort and fishing mortalities.

Instead, the model was tuned by basing the availability coefficients (q_s) on those used in the WCPOBTM model and finding the effort levels that most successfully reproduce the catch shares taken by the main fleets in 2005, whereafter the initial recruitment to each stock was determined by setting the catch produced by the model equal to the total catch in 2005.[1] Table 1 shows the fleets identified for the purpose of this study and the catches taken of bigeye, yellowfin and skipjack in 2005, and Figure 2 the actual catches of the fleets in 2005 and the catches implied by the said procedure.

A further reality check of the parameters is provided by looking at the survival rate of fish in the three stocks resulting from the effort produced by this procedure. In the WCPOBTM model the life-span of fish in the three stocks is set at 32 quarters for bigeye (8 years), 22 for yellowfin (5.5 years), and 16 for skipjack (4 years). The implication is that few fish survive to this age. With the effort set as explained above, about six percent of each age group survives to the said ages. This is probably realistic; according to Hampton et al. (2006a, b), a significant number of bigeye survive to the age of eight years, and a significant number of yellowfin to the age of four, according to tagging experiments. With the parameters above, 11 percent of yellowfin survive until the age of four. Whether or not six and 11 percent is significant can be debated, but a lower survival rate implies overexploitation and much greater gains from reducing fishing effort than this tuning of the model gives rise to.

Table 1: Catches of tuna (thousand tonnes) in 2005 in the western and central Pacific by fleet and stock.

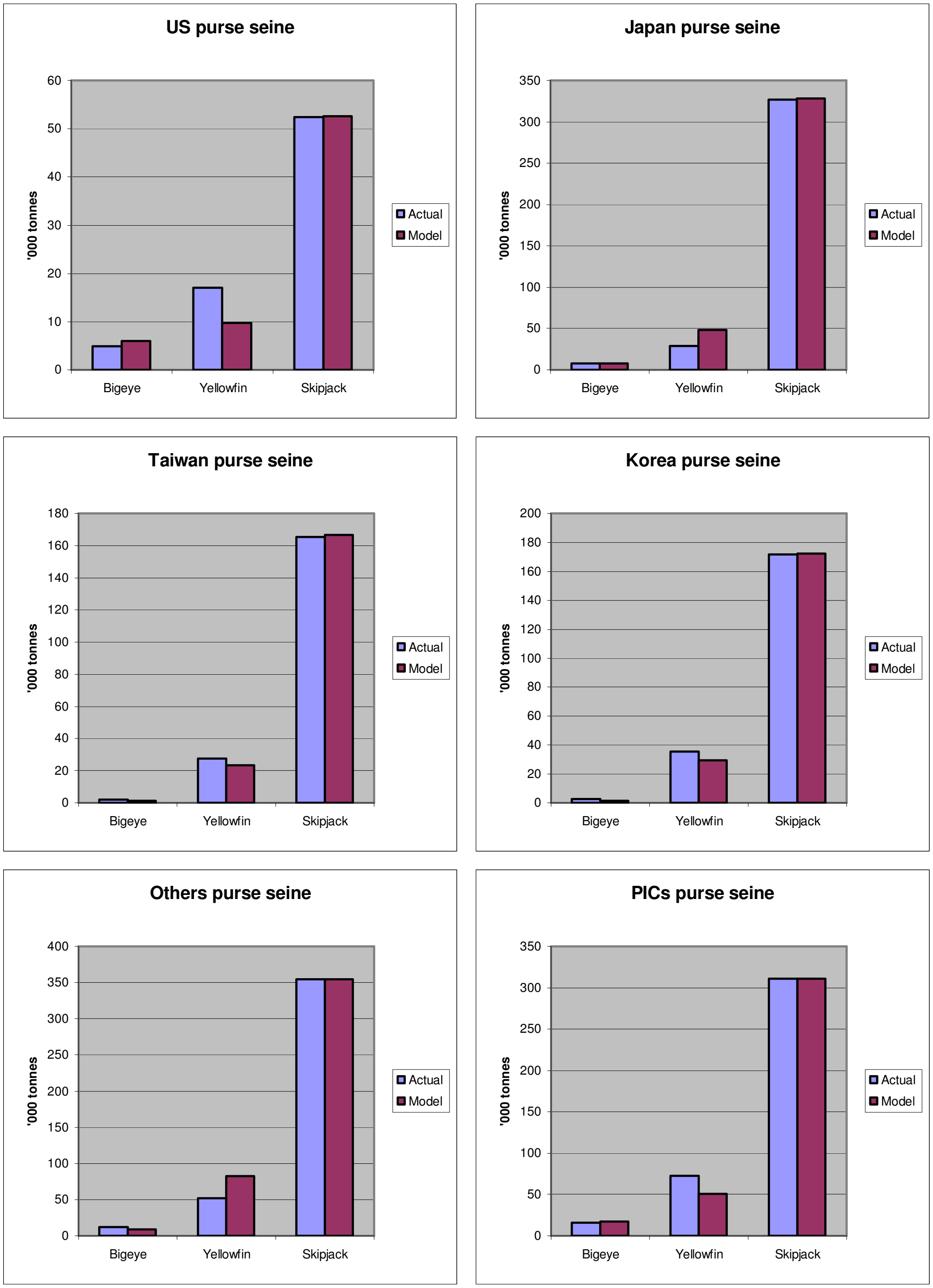
Purse seine (including pole and line)				Longline			
	Bigeye	Yellowfin	Skipjack		Bigeye	Yellowfin	Skipjack
US	4.8	17.0	52.4	China	30.4	15.7	0.1
Japan	8.1	29.3	327.1	Japan	15.3	20.2	3.5
Korea	2.6	35.6	171.6	Korea	6.4	2.4	0.0
Taiwan	2.2	27.6	165.3	Taiwan	15.6	13.3	0.0
Others	17.2	52.4	354.3	Others	17.2	22.9	1.5
Pacific Islands	16.0	72.9	311.0				
Total	50.9	234.9	1381.6	**Total**	84.9	74.5	5.1

Source: Secretariat of the Pacific Community: Tuna Yearbook 2005.

The model used here, as well as the WCPOBTM model, imply non-selective fishing with respect to stocks; once the gear has been set the fixed availability coefficients and the abundance of the stocks determine how much will be caught from each stock. Technically this means that any given effort by the *k*-th fleet of purse seiners or longliners will produce fishing mortalities for the three stocks according to the relationship $f_{i,s,k} = q_{s,k} s_{i,s,k} E_k$. Model availability and selectivity coefficients are given in Tables A1 and A2 in the Appendix.

The different national fleets have different q_i's, as their catch shares differ between stocks. The differences in the q_i's indicate that a total absence of selectivity between stocks is not quite true, although it may be due to different fleets fishing in different areas rather than targeting certain stocks, except indirectly by fishing in certain areas rather than others.

[1] The WCPOBTM model identifies two different long line fleets, one for frozen and one for fresh tuna. We have used the *q*'s for fresh tuna, except for Korea, which is not represented with a fleet for fresh tuna in the model. For Korea we used the same *q* as for Japan. For fisheries other than purse seining and longlining the fishing mortality was determined for each stock separately by reproducing the catches in these fisheries. The selectivity pattern for the Indonesian domestic fisheries was used, but this fishery, as well as the Philippine domestic fishery (which has a somewhat different selectivity pattern) is an important part of these other fisheries.


US purse seine
Japan purse seine
Taiwan purse seine
Korea purse seine
Others purse seine
PICs purse seine
'000 tonnes
Actual
Model
Bigeye
Yellowfin
Skipjack

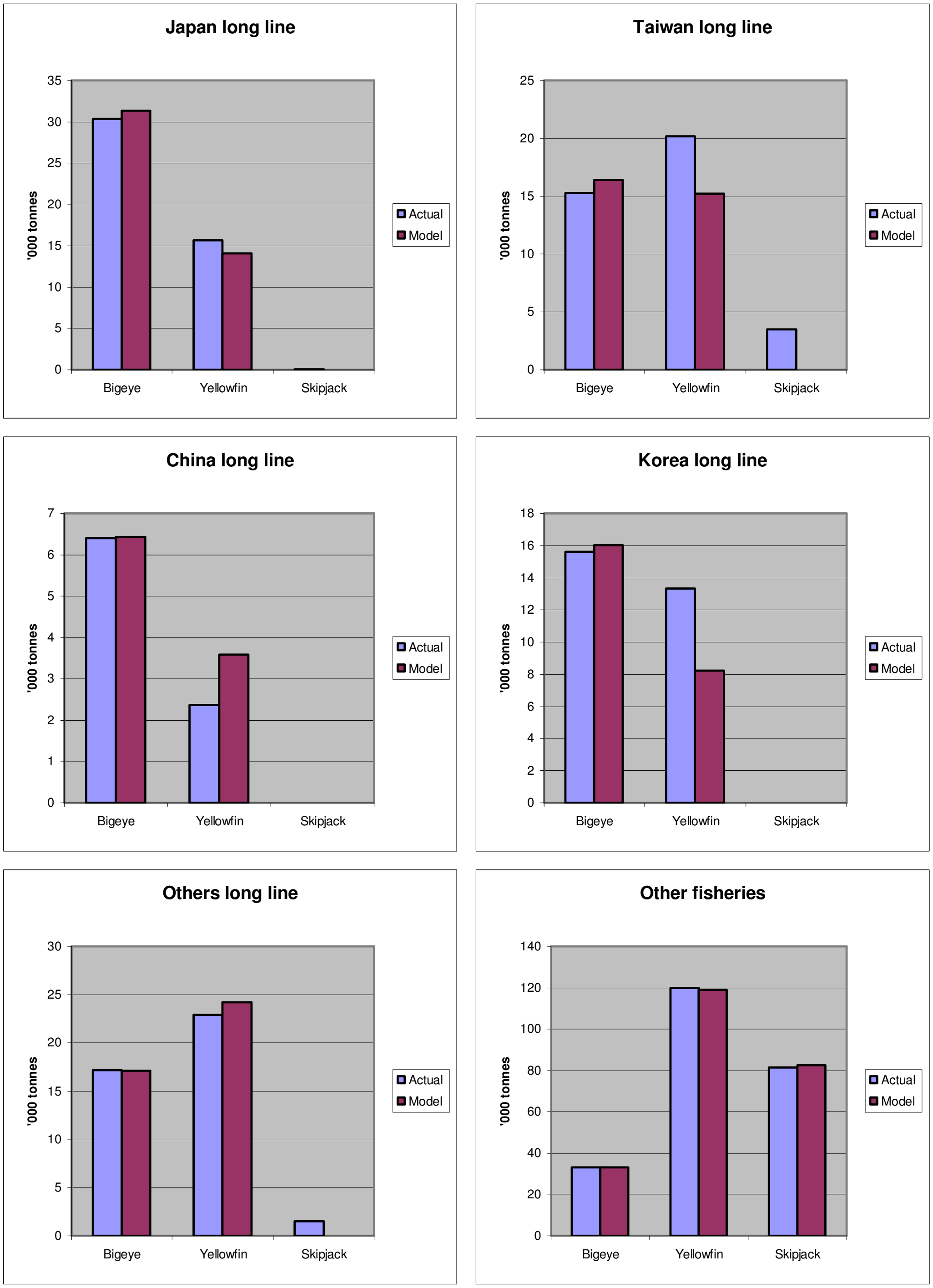


Figure 2: Actual and simulated catches of tuna for 12 fleets.

ECONOMIC ANALYSIS

For economic analysis, it is necessary to determine the cost per unit of effort for the different fleets. As a point of departure we use the cost parameters of the WCPOBTM model, but this is not unproblematic, as our model excludes one of the stocks included in the WCPOBTM model. Furthermore we have calculated the effort levels for the different fleets by reproducing the 2005 catches in the best possible way rather than using actual effort data for the different fleets. Since the cost figures of the WCPOBTM model presumably reflect the best estimates of the cost differences between the different fleets we deal with this by scaling all the cost figures by the same factor so that a reasonable rent is produced for the different fisheries. As to prices, these are fixed and equal to unity for the purse seine fishery, but 10 and 6, respectively, for bigeye tuna and yellowfin tuna caught with longline. This price difference is set on the basis of Bertignac et al. (2001), which reported price differentials of approximately this magnitude between the purse seine and the longline fishery.

A reference solution

The rent resulting from using the 2005 catches as a reference solution is shown in Table 2. The US purse seine fleet breaks even, and long lining by Others returns a small loss. For the remaining fleets we get positive and quite possibly unrealistically high rents; China and Taiwan produce a rent of over 30 percent of production value, Japan about 26 in the longline fishery and 10 in the purse seine fishery, and Korea about 20 percent in the longline fishery and 16 in the purse seine fishery. The Pacific island countries get a rent of 7 percent in their purse seine fisheries. Since the distant water fishing fleets pay fees for access to the economic zones of the Pacific island nations, it is reasonable to expect some rents in these fisheries, for otherwise the boatowners would be making a capital loss and would not renew their boats when they are worn out. These access fees are only 3-4 percent of revenues (Petersen, 2002), however, while the rents in Table 2 are much higher than needed for that, except for the US fleet, which just breaks even. There is reason to expect, therefore, that the cost of the US fleet is lower than assumed here, a point we will return to below.

Table 2: Implied rent in the tuna fisheries in 2005 as percent of production value.

Purse seine; Pole & line					Longline					
US	Japan	Korea	Taiwan	Others	PICs	Japan	Taiwan	China	Korea	Others
0.0	10.5	16.4	32.1	27.2	7.0	26.6	34.5	34.3	21.9	-1.3

Maximizing rents

Table 3 compares the solution maximizing aggregate rents and the reference solution. In the rent-maximizing exercise, the mortality in the other fisheries is held constant, and they are not a part of the rent maximization. The aggregate rent is the maximum, undiscounted, sustainable rent, as the model is a static yield per recruit model that compares different long term equilibrium solutions, but including the dynamics between age groups. There is a large reduction in fishing mortality in the purse seine fishery while the mortality in the longline fishery increases by 150-160 percent. As a result, purse seine catches of bigeye and yellowfin decrease by about 70 and 30 percent, respectively, while the decrease in the catch of skipjack is relatively limited, or about 10 percent. Longline catches of bigeye and yellowfin more than double. The rent increases in both fisheries; as a percent of revenue it nearly doubles in the purse seine fishery (total revenue declines), and in the longline fishery it increases from about 20 to 30 percent of revenue. These increases in rent are in part due to the exclusion of high cost fleets; the only fleet active in the purse seine fishery is Taiwan while both Taiwan and China are active in the longline fishery.

Table 3: Comparison of rent-maximizing and reference solution.

Species	Purse seine			Longline		
	Reference	Rent max	Change (%)	Reference	Rent max	Change (%)
		f			*f*	
Bigeye	0.046	0.012	-73.8	0.008	0.020	146.2
Yellowfin	0.025	0.018	-28.0	0.003	0.007	160.9
Skipjack	0.031	0.028	-9.9	0	0	
		Catch			Catch	
Bigeye	43.2	10.4	-75.8	87.4	199.1	127.9
Yellowfin	244.8	174.8	-28.6	65.3	168.5	157.9
Skipjack	1385.8	1267.5	-8.5	0	0	
		Rent			Rent	
All	283.2	478.2	68.8	265.1	921.9	247.8
		Rent as % of revenue			Rent as % of revenue	
All	16.9	32.9		20.9	30.7	
		Fleets active			Fleets active	
	All	*Taiwan*		*All*	*Taiwan, China*	

It is noteworthy that both the purse seine fishery and the longline fishery appear in the rent-maximizing solution. It would not have been unexpected if the purse seine fishery had disappeared altogether, the reason being that each fleet fishes all three species indiscriminately. The longline fishery obtains much higher prices for its product, and it makes sense to limit the purse seine fishery for the benefit of the longline fishery, unless the costs in the longline fishery are high enough to make up for the price difference. This is what happens in the rent-maximizing solution, as we have seen; the fishing mortality in the purse seine fishery goes down and increases in the longline fishery. But the reduction of effort in the purse seine fishery is bound to also hit the skipjack fishery, because of the indiscriminate fishing of all three stocks, even if there is no longline fishery for skipjack.[2] Letting the Taiwanese fleet fish do the purse seining achieves a judicious compromise; it turns out that the selectivity of the Taiwanese purse seiners is such as to take relatively little of bigeye and yellowfin compared to skipjack. Figure 3 shows the selectivity pattern for bigeye and yellowfin of the six purse seine fleets in the model, relative to skipjack.

As already indicated, the advantage of the longline fleet is due to the higher prices obtained for the fish it catches, which goes to the Japanese sashimi market. There is good reason to expect the price of fish sold into that market to decline the more fish that is supplied; this was one of things analysed by Bertignac et al. (2001). We shall not here consider the elasticity of

[2] In reality there is some long line fishing for skipjack, as can be seen from Figure 1, but it is very small and has been ignored here for simplicity.

demand in the Japanese sashimi market, but instead investigate by how much the price of fish in the longline fishery would have to fall to make this fishery unprofitable, from the point of view of maximizing aggregate rents. If the price advantage of the longline fishery is reduced by 40 percent, the Taiwanese longline fleet disappears from the rent-maximizing solution, and only the Chinese fleet is left. If the price advantage for the longline fleet falls by 50 percent, it disappears from the rent-maximizing solution altogether.

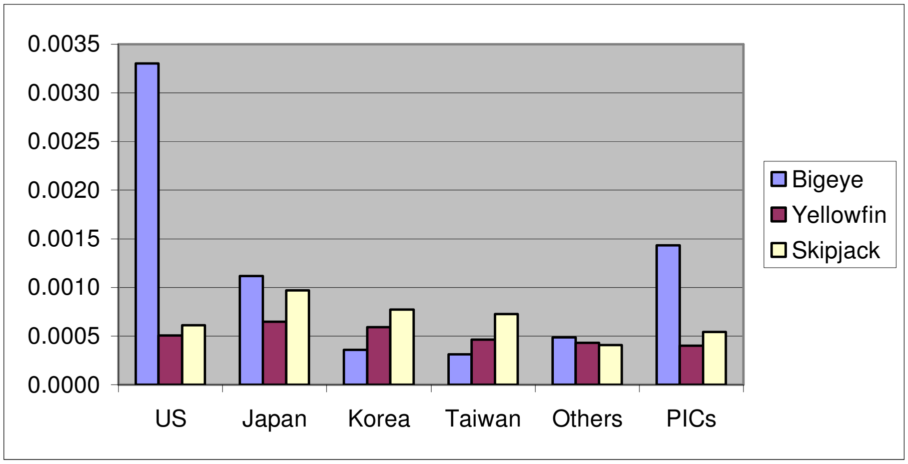


Figure 3: Selectivity of the six purse seine fleets.

How would a revenue-maximizing solution differ from the rent-maximizing solution? This is interesting, because if there is no stock effect (i.e., the catch per unit of effort is constant and independent of the stock size), the cost per unit of fish caught a constant. This means that the revenue-maximizing solution would be identical to the rent-maximizing solution for cases where tuna prices are the same as unit tuna rents . This solution is not radically different from the rent-maximizing solution already discussed; the Taiwanese purse seiners would still be the only ones fishing and would do so on a greater scale, and the fishing mortality in the longline fishery would be much higher, with the fishing being done by the most cost-efficient fleet. One might have suspected that the fishing mortality would become infinitely large in this solution. This can easily happen in models like this with a fixed price, unless the selectivity pattern is such that fishing with high intensity would deplete the age groups well before they have reached the maximum biomass weight.

Stability of the grand coalition

Solutions like the rent-maximizing solution above are none too likely to be attained. They imply that the most efficient fleets should do the fishing and the others disappear, with the latter being compensated by a share in the greater profit. Such grand coalitions are sometimes not viable even in principle, as there may be incentives for some members of the coalition to break out and form their own sub-coalition, either with themselves as a single member or with more, but not all, members. See Kennedy (2003) for consideration of solution concepts, with and without side-payments, and allocations to indicate the security of coalitions.

The nature of the rent π_k accruing to the k-th fleet breaking out can be explained as follows. The k-th one-member coalition (i.e., fleet) acts as a leader and solves the problem:

$$\max_{f_k} \pi_k\{\boldsymbol{f}_k \mid \boldsymbol{x_0}\} \tag{4}$$

where π_k is the rent generated, $\boldsymbol{f}_k$ are the fishing mortalities set and $\boldsymbol{x_0}$ is the array of stock vectors of numbers in each age category at the beginning of the fishing season prior to fishing.

Let $\boldsymbol{f}_k^*$ denote the solution to (4). The remaining fleets indexed by j act together as a group follower, solving the problem:

$$\begin{aligned} &\max_{\boldsymbol{F}_J} \pi_J\{\boldsymbol{F}_J \mid \boldsymbol{f}_k^*, \boldsymbol{x_0}\} \\ &\text{where } \boldsymbol{F}_J = \text{ the set of } \boldsymbol{f}_j \ \forall\, j \neq k \\ &\text{and } \boldsymbol{f}_k^* \text{ is the solution to the } k\text{-th fleet's problem, acting as leader.} \end{aligned} \tag{5}$$

This is one thing that could threaten the grand coalition implied by the rent-maximizing solution. Each country would have to be offered an outcome at least as good as the country could obtain if it decided to break out of the coalition and maximize its own rent. Table 4 shows that the sum of what the individual countries could obtain from a one-country coalition is greater than the maximal rent.[3] Looked at in another way, suppose it is agreed that a nation's fair share of the rent is determined by its contribution to making the coalition complete. The column "fair" rent share in Table 4 shows what each nation would then get. With these payments, in this case, all fleets would gain more by going it alone than by accepting their "fair" share. To this extent the grand coalition is unstable. This will be the case whenever the total of leader rents exceeds max rent.

[3] The US and "others" are not represented in the table because the profitability of their fisheries in the reference solution is marginal or sub-marginal, and they drop out of the coalition game.

Table 4: Rent obtained by a one-member coalition and a "fair" share for the individual countries.

Each fleet considers acting first to maximise its rent, leaving the rest to maximise their joint rent	Leader fleet rent	"Fair" rent share of Max rent
Japan	145.5	141.6
Korea	153.1	149.0
Taiwan	822.5	800.4
PICs	24.6	23.9
China	293.0	285.1
Total	**1438.7**	**1400.1**
All fleets act to maximise joint rent cooperatively		
Max rent	**1400.1**	

There are conditions, however, under which this coalition would nevertheless be stable. This occurs if all countries realize that if one of them breaks out, all the others would do likewise. What then is important to look at is the temporary gain one country might obtain from breaking out of the coalition less the present value of the discounted loss resulting from everyone else going for the Nash equilibrium solution. The outcome of this depends on the discount rate and would require an intertemporal model to analyse (Hannesson, 1997).

The Nash equilibrium

Given that a grand coalition is none too likely, it makes sense to look at a solution where everyone is competing against everyone else, i.e., a Nash equilibrium with seven participants, the participants being defined as the five countries US, Japan, Taiwan, Korea, and China, plus the Pacific island countries as one player, and all others as the seventh player.

For the Nash Equilibrium, the following set of solutions to all one-member coalition problems holds:

$$\begin{array}{c} \max_{f_k} \pi_k\{\boldsymbol{f}_k \mid \boldsymbol{F}_J^*, \boldsymbol{x_0}\} \\ \text{where } \boldsymbol{F}_J^* = \text{ the set of } \boldsymbol{f}_j^* \ \forall\, j \neq k. \end{array} \quad \forall k \qquad (6)$$

Table 5 compares the Nash equilibrium with the reference solution. The US, Japan and the Pacific island countries drop out of purse seining, and Korea and Others drop out of longlining. Japan reduces its longlining by 20 percent but loses almost all its rent from the fishery. Korea increases its purse seining by 30 percent, but loses more than 80 percent of its rents. Others expand their activities in purse seining and increase their rents by almost 60 percent, but drop out of longlining, where they operated with a loss in the reference solution. Taiwan expands its activities in purse seining and longlining six- to sevenfold and increases its rents in the purse seine fishery by 300 percent and doubles its rents in the longline fishery. China expands its efforts in the longline fishery 16-fold and increases its rents by 400 percent. The total rent is only a half of what it is in the rent-maximizing solution, but actually three times higher than in the reference solution.

Table 5: Effort in the Nash equilibrium, relative to the reference solution, and percentage change in rents from the reference solution.

	Purse seine; and Pole & line						Longline				
	US	Japan	Korea	Taiwan	Others	PICs	Japan	Taiwan	China	Korea	Others
Effort	0	0	1.3	7.2	3.5	0	0.8	6.4	16.4	0	0
Rent, % change	100	-100	-84.7	304.0	57.5	-100	-91.2	92.2	402.3	-100	100

More realistic costs?

This Nash equilibrium looks suspicious; one would expect this to be the bottom line below which we would not be likely to fall. Some fleets, such as US purse seiners, purse seiners from the Pacific island countries, and Korean and Others' longliners, are conspicuously absent from the Nash equilibrium. One suspects that this could be due to the costs for these fleets being set too high. Let us therefore look at a solution where the cost per unit of effort has been reduced to allow these fleets (except for Others' longliners) to appear in the Nash equilibrium solution. The result is summarized in Table 6. With the cost per unit of effort being reduced by 20 percent for purse seiners from the US and the Pacific island countries, and Korean longliners, these fleets are now represented in the solution. A cost reduction of 30 percent for Others' longliners was not enough, however, for this fleet to appear in the Nash equilibrium solution.

Table 6: Nash equilibrium compared with the reference solution, with changed cost per unit of effort. Percentage change in cost per unit of effort (US, PICs, and Korean longliners: 20 percent; Japanese longliners: 10 percent; other longliners: 30 percent).

	Purse seine; and Pole & line						Longline				
	US	Japan	Korea	Taiwan	Others	PICs	Japan	Taiwan	China	Korea	Others
Effort	1.3	0	0	8.2	2.6	2.6	1.0	2.7	6.2	4.7	0
Rent, % change	-95.4	-100.0	-100.0	261.7	-18.3	-30.5	-91.0	-66.7	-35.4	-16.9	100.0

We now make comparisons with the reference solution and the rent-maximizing solution, given these new costs. The effort by the US fleet increases by 30 percent compared with the reference solution, but the rent almost disappears. Purse seining both by the Pacific island countries and Others is increased more than two and a half times, but rents fall by 30 and 18 percent, respectively. Taiwan increases its longlining almost threefold and its purse seining more than eightfold, increasing rents in purse seining by 260 percent while they fall by almost 70 percent in longlining. Korea increases its longlining almost fivefold, but rents fall by 17 percent. China increases its longlining more than sixfold, but rents fall by 35 percent. In this case the Nash equilibrium results in about 40 percent lower rents than the reference solution, and about 60 percent lower rents than the rent-maximizing solution.

The rent-maximizing solution differs from the previous one in that more longline fleets now are represented. In the previous one only Taiwan and China were represented, but now also Korea and Others are included. Japanese costs are still too high. Still it is only Taiwan that does the purse seining, on about the same scale as before.

CONCLUSION

This paper has shown that considerable, but not dramatic, increases in rent can be obtained from changing the tuna fishery from its present configuration. Two changes are involved. First, purse seining should be reduced drastically, for the benefit of the longline fishery, which delivers a more valuable product. The price advantage of the longline fishery would have to be reduced by a half to overturn this conclusion.

Second, provided there is a mechanism to share the aggregate rent, the fishing should be carried out by the most cost-effective fleets. This means that some fleets would disappear altogether, with the nations involved getting a share of the total rent. There are obvious practical and political obstacles to such a solution; how long would a country without any fishing fleet of its own be considered entitled to a share in the rents of a fishery taking place hundreds of miles away from its economic zone? Apart from that, in this particular setting this kind of solution would probably not be stable; there is no way that all countries can be offered rent shares that exceed what they could get on their own if one breaks out of the coalition and the others stay in it. Only if they realize that a breakdown of the coalition would end in everybody competing against everyone else and that the gains from breaking away would be temporary could the grand coalition be viable.

Furthermore, the result that only the Taiwanese fleet remains in the purse seine fishery in the rent-maximizing solution illustrates that the purse seine fishery should be cut back in a way that minimizes the impact on the skipjack fishery and maximizes the impact on the yellowfin and especially the bigeye stocks. To the extent it is possible for the purse seine fishery to selectively fish the different stocks they should go for the skipjack and leave the yellowfin and the bigeye alone.

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Appendix

Table A1: Availability coefficients $q_{s,k}$ by species s and fleet k
(All to 3 significant figures)

	Purse seine and Pole & line					
	US	Japan	Korea	Taiwan	PICs	Others
Bigeye	0.003300	0.001120	0.000361	0.000315	0.000645	0.001650
Yellowfin	0.000508	0.000647	0.000595	0.000465	0.000401	0.000429
Skipjack	0.000772	0.000940	0.000887	0.000798	0.000623	0.000319

	Longline				
	China	Japan	Korea	Taiwan	Others
Bigeye	0.000002190	0.000003010	0.000003010	0.000002250	0.000001210
Yellowfin	0.000000557	0.000000616	0.000000216	0.000000953	0.000000780
Skipjack	0	0	0	0	0

Table A2: Selectivity coefficients $s_{i,s,k}$ by age i, species s and fleet k

Skipjack
Selectivity coefficients for first quarter of each year class

	1	5	9	13
Purse seiners, all fleets	0.002	0.631	0.386	0.630
Pole and line, all fleets	0.000	0.315	0.529	0.722
Longline, frozen and fresh, all fleets	0.001	0.007	0.222	0.995

Yellowfin
Selectivity coefficients for first quarter of each year class

	1	5	9	13	17
Purse seiners, all fleets	0.027	0.428	0.467	0.326	0.382
Pole and line, all fleets	0.027	0.428	0.467	0.326	0.382
Longline, frozen and fresh, all fleets	0.004	0.047	0.941	0.993	0.999

Bigeye
Selectivity coefficients for first quarter of each year class

	1	5	9	13	17	21	25
Purse seiners, all fleets	0.011	0.587	0.091	0.016	0.032	0.068	0.095
Pole and line, all fleets	0.011	0.587	0.091	0.016	0.032	0.068	0.095
Longline, frozen and fresh, all fleets	0.008	0.104	0.825	0.999	0.987	0.981	0.981