Updated MULTIFAN-CL based assessment of yellowfin tuna

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Background

Biology

Yellowfin tuna are distributed throughout the tropical and sub-tropical waters of the Pacific Ocean. However, there is some indication of restricted mixing between the western and eastern Pacific based on analysis of genetic samples (Ward et al. 1992) and tagging data (Figure 1). Adults (larger than about 100 cm) spawn, probably opportunistically, in waters >26°C (Itano 2000), while juvenile yellowfin are first encountered in commercial fisheries (mainly surface fisheries in Philippines and eastern Indonesia) at several months of age.

![Figure 1. Movements of tagged yellowfin tuna.](image)

Yellowfin tuna are relatively fast growing, and have a maximum fork length (FL) of about 180 cm. The growth of juveniles departs from von Bertalanffy type growth with the growth rate slowing between about 40 and 70 cm FL (Lehodey and Leroy 1999).

The natural mortality rate is strongly variable with size, with the lowest rate of around 0.6–0.8 yr⁻¹ being for pre-adult yellowfin 50–80 cm FL (Hampton 2000). Tag recapture data indicate that significant numbers of yellowfin reach four years of age. The longest period at liberty for a recaptured yellowfin tagged in the western Pacific at about 1 year of age is currently 6 years.

Fisheries

Yellowfin tuna, an important component of tuna fisheries throughout the western and central Pacific Ocean (WCPO, east of 150°W), are harvested with a diverse variety of gear types, from small-scale artisanal fisheries in Pacific Island and southeast Asian waters to large, distant-water longliners and purse seiners that operate widely in equatorial and tropical waters. Purse seiners catch a wide size range of yellowfin tuna, whereas the longline fishery takes mostly adult fish.

Since 1990, the yellowfin tuna catch in the WCPO has varied between 350,000 – 460,000 mt (Figure 2). The 1997 catch in the WCPO was the largest on record (460,000 mt), with the estimated 1998 catch only slightly lower (446,000 mt). The elevated total catch in these most recent years followed the lowest catch for seven years in 1996, a result of greatly reduced purse-seine catches. Purse seiners harvest the majority of the yellowfin tuna catch (56% by weight in 1997–1998), with the longline and pole-and-line fisheries comprising 16% and 3% of the total catch, respectively. Yellowfin tuna usually represent ~20–25% of the
overall purse-seine catch and may contribute higher percentages of the catch in individual sets. Yellowfin tuna are often directly targeted by purse seiners, especially as unassociated schools.

The longline catch in recent years (60,000–80,000 mt) is well below catches in the late 1970s to early 1980s (90,000–120,000 mt), presumably related to changes in targeting practices by some of the larger fleets. Catches in the ‘Other’ category in Figure 2 are largely composed of yellowfin tuna from the Philippines and eastern Indonesia. These catches come from a variety of gear types (e.g., ring net, bagnet, gillnet, handline and seine net) and have increased steadily over time.

Figure 2. WCPO yellowfin tuna catch, by gear.

Figure 3 shows the spatial distribution of yellowfin tuna catch in the WCPO for the past ten years. The majority of the catch is taken in equatorial areas, with declines in both purse-seine and longline catch towards the east. Also, the east-west distribution of catch is strongly influenced by ENSO events, with larger catches taken east of 160°E during *El Niño* episodes.
Figure 3. Distribution of yellowfin tuna catch, 1988–1998. The dotted lines indicate the spatial stratification used in the MULTIFAN-CL model.

Data compilation

The data used in the yellowfin tuna assessment consist of catch, effort and length-frequency data for the fisheries defined in the analysis, and tag release-recapture data. The details of these data and their stratification are described below. These data may be downloaded for independent review and analysis. <click here to download data files (yft.frq, yft.tag)>

Spatial stratification

The geographic area considered in the assessment is the WCPO, defined by the coordinates 40°N–35°S, 120°E–150°W. Within this overall area, a seven-region spatial stratification was adopted for the assessment (Figure 3). This stratification has been used by the Yellowfin Research Group of the Standing Committee on Tuna and Billfish in recent years for compilation of statistics and fishery monitoring.

Temporal stratification

The time period covered by the assessment is 1962–1998. Within this period, data were compiled into quarters (Jan–Mar, Apr–Jun, Jul–Sep, Oct–Dec).

Definition of fisheries

MULTIFAN-CL requires the definition of “fisheries” that consist of relatively homogeneous fishing units. Ideally, the fisheries so defined will have selectivity and catchability characteristics that do not vary greatly over time (although in the case of
catchability, some allowance can be made for time-series variation). However, it is seldom practicable or even necessary to stratify the data into a large number of fisheries so as to isolate all variability in these parameters. More fisheries means more parameter complexity, so a parsimonious approach is required. For most pelagic fisheries assessments, fisheries defined according to gear type, fishing method and region will usually suffice. The sixteen fisheries defined for the purpose of this assessment are as follows:

<table>
<thead>
<tr>
<th>Fishery #</th>
<th>Nationality</th>
<th>Gear</th>
<th>Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Philippines</td>
<td>Ringnet</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>Philippines</td>
<td>Handline</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>Indonesia</td>
<td>Various</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>All</td>
<td>Purse seine, associated sets</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>All</td>
<td>Purse seine, unassociated sets</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td>All</td>
<td>Purse seine, associated sets</td>
<td>4</td>
</tr>
<tr>
<td>7</td>
<td>All</td>
<td>Purse seine, unassociated sets</td>
<td>4</td>
</tr>
<tr>
<td>8</td>
<td>All</td>
<td>Purse seine, associated sets</td>
<td>5</td>
</tr>
<tr>
<td>9</td>
<td>All</td>
<td>Purse seine, unassociated sets</td>
<td>5</td>
</tr>
<tr>
<td>10</td>
<td>All</td>
<td>Longline</td>
<td>1</td>
</tr>
<tr>
<td>11</td>
<td>All</td>
<td>Longline</td>
<td>2</td>
</tr>
<tr>
<td>12</td>
<td>All</td>
<td>Longline</td>
<td>3</td>
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<td>13</td>
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<td>Longline</td>
<td>4</td>
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<tr>
<td>15</td>
<td>All</td>
<td>Longline</td>
<td>6</td>
</tr>
<tr>
<td>16</td>
<td>All</td>
<td>Longline</td>
<td>7</td>
</tr>
</tbody>
</table>

**Catch and effort data**

Catch and effort data were compiled according to the fisheries defined above. All catches were expressed in numbers of fish. Effort data for the Philippines and Indonesian fisheries were unavailable and defined as “missing”. Effort data for purse seine fisheries is defined as days fishing and/or searching, allocated to set types based on the proportion of total sets attributed to a specified set type (associated or un-associated sets) in logbook data. For the longline fisheries, we used estimates of “effective” effort derived in a separate study (Bigelow et al. 1999). Essentially, “effective” effort is an estimate of the numbers of longline hooks fishing in the mixed layer above the thermocline, which is believed to define yellowfin tuna habitat. The estimates take into account the time and spatial variability in the depth of the mixed layer (using oceanographic databases) and variation in the fishing depth of longliners as indicated by distributions of the numbers of hooks between floats. The effective effort estimates were derived at 5°-month resolution separately for the Japanese, Korean and Taiwanese distant-water longline fleets. The estimates were then summed across these fleets and raised to represent the total longline catch by 5°-month before aggregating into the seven-area-quarterly stratification used in the model. Within the model, effort for each fishery was normalized to an average of 1.0 to assist numerical stability. In the case of the longline fisheries, the normalization occurred over all seven fisheries rather than individually. Also, longline effort in each fishery was divided by the relative size of the respective region. The application of these procedures allowed longline CPUE to index exploitable abundance in each region (rather than density), which in turn allowed simplifying assumptions to be made regarding the spatial and temporal constancy of catchability for the longline fisheries (see below).

Catch and CPUE for each fishery are shown in Figure 4. The source data used in the compilation of catch and effort data was a database maintained by the OFP at a 5 degree square, month resolution. This database, known internally in the OFP as “BEST”, has accumulated data from a variety of sources, processed them into a common format, and raised
them so as to represent the best estimates of total catches as presented in the most recent version of the SPC Tuna Fishery Yearbook.

The specifics of the source and treatment of catch and effort data in “BEST” that are relevant to the yellowfin tuna assessment are as follows:

**Philippines and Indonesian domestic fisheries** (fisheries 1, 2). The only data available for the domestic fisheries of Philippines and Indonesia are the estimates of total annual catches contained in the SPC Tuna Fisheries Yearbook. Estimates of catches in number have been derived from average weights estimated from available size composition data. The spatial distribution of catches has been estimated from a variety of data, including data from the Landed Catch and Effort Monitoring Programme in the Philippines as well as more general information on the distribution of the fisheries.

**Purse seine** (fisheries 4–9). Purse seine catches for the Japanese and Korean fleets have been provided by the National Research Institute of Far Seas Fisheries (NRIFSF) of Japan and the National Fisheries Research and Development Institute (NFRDI) of the Republic of Korea, respectively at 1 degree square, month resolution. Data for the Japanese fleet are available to 1999, while the data submitted by Korea are current only to 1995. Catches for the Korean fleet since 1995 have been estimated from logbook data raised to estimates of the total catch. Catches for all other fleets have been estimated from logbook data raised to estimates of the total catch. Catch numbers have been derived using average weights derived from length-frequency samples (stratified by associated and unassociated types), where the sample weights were calculated using a length-weight relationship (estimated from length-weight samples). The average weight table was constructed at 5°-month resolution where a length frequency sample of at least 100 fish was available. If such a sample was not available, the resolution was relaxed in a set sequence until the required sample was obtained.

**Longline** (fisheries 10–16). Catch and effort data for the Japanese, Korean and Taiwanese fleets have been provided by NRIFSF, NFRDI and the National Taiwan University (1967–1993) and the Overseas Fisheries Development Council of the Republic of China (OFDC) through the Council of Agriculture (1994–1996), respectively. Most of the data has been provided at 5 degree square, month resolution and has been raised to represent total catches. Where data have not conformed to this format, the OFP has applied average spatial and temporal catch distributions to transform the data. Data for longline fleets of SPC member countries have generally been provided in raw logbook form, which have been aggregated and raised to represent total catches at 5 degree square, month resolution.
Length-frequency data

Available length-frequency data for each of the defined fisheries were compiled into 100 2-cm size classes (10–12 cm to 208–210 cm). Each length-frequency observation consisted of the actual number of yellowfin tuna measured. Samples were not available for all fisheries for all periods (Figure 5). Fortunately, the MULTIFAN-CL model does not require that this be the case.

The data were collected from a variety of sampling programmes, which can be summarized as follows:
Philippines and Indonesia: Size composition data for the Philippines and Indonesia domestic fisheries are restricted to a sampling programme conducted in the Philippines in 1993–94 and, for Indonesia, catches by the SPC tagging vessels in 1980 and 1991–93.

Purse seine: Length-frequency samples from purse seiners have been collected from a variety of port sampling programmes since the mid-1980s. Most of the early data is sourced from the U.S. National Marine Fisheries Service (NMFS) port sampling programme for U.S. purse seiners in Pago Pago, American Samoa and an observer programme conducted for the same fleet. Since the early 1990s, port sampling and observer programmes on other purse seine fleets have provided additional data. Only data that could be classified by associated and unassociated set types were included in the final data set.

Longline: The majority of the historical data were collected by port sampling programmes for Japanese longliners unloading in Japan and from sampling aboard Japanese research and training vessels. It is assumed that these data are representative of the sizes of longline-caught yellowfin generally in the WCPO. In recent years, data have also been collected by OFP and national port sampling and observer programmes in the WCPO.

Tagging data

A large amount of tagging data was available for incorporation into the MULTIFAN-CL analysis. The data used consisted of yellowfin tuna tag releases and returns from the OFP’s Regional Tuna Tagging Project <link to tagging page> conducted during 1989–1992. Tags were released using standard tuna tagging equipment and techniques by trained scientists and technicians. The tag release effort was spread throughout the tropical western Pacific, between approximately 120°E and 170°W (see Kaltongga 1998 <link to publication> for further details).

For incorporation into the MULTIFAN-CL analysis, tag releases are stratified by release region (all yellowfin tuna releases occurred in regions 3, 4 and 5), time period of release (quarter) and the same size classes used to stratify the length-frequency data. A total of 39,423 releases were classified into 26 tag release groups in this way. The returns from each size class of each tag release group (4,025 tag returns in total) were then classified by recapture fishery and recapture time period (quarter).
Figure 5. Yellowfin tuna fishery data. The upper blue line indicates periods where a fishery (i.e. catches) occurred. The pink line indicates the availability of effort data. The red crosses indicate years in which at least 400 fish were measured.

Structural assumptions of the model

As with any model, various structural assumptions have been made in the yellowfin tuna model. Such assumptions are always a trade-off to some extent between the need, on the one hand, to keep the parameterization as simple as possible, and on the other, to allow sufficient flexibility so that important characteristics of the fisheries and population are captured in the model. The mathematical specification of structural assumptions is given in the <MULTIFAN-CL methodology> page. The main structural assumptions used in the yellowfin model are discussed below.

Modeling the tagging data

The tag releases are internally assigned to age classes on the basis of the distributions of age-at-length determined from the growth parameters of the model. This is done dynamically during each function evaluation. For each time period following release, the model then predicts the number of recaptures by fishery on the basis of the parameters of the age-structured model. The recaptures are kept separate for each release set for the first ten quarters, after which they join a pooled population in which the original release set identity is lost. This compromise was made in order to extract the maximum information from the tag data in a computationally efficient way.

While the model has the capacity to estimate tag-reporting rates, we provided Bayesian priors for fishery-specific reporting rates. Relatively informative priors were provided for reporting rates for the Philippines and Indonesian domestic fisheries and the purse seine fisheries, as independent estimates of reporting rates for these fisheries were
available from tag seeding experiments and other information (Hampton 1997). For the longline fisheries, we have no auxiliary information with which to estimate reporting rates, so relatively uninformative priors were used for these fisheries – the reporting rates were essentially independently estimated by the model. A likelihood component for the tag data was computed using a Poisson distribution.

Recruitment

“Recruitment” in terms of the MULTIFAN-CL model is the appearance of age-class 1 fish in the population. Earlier attempts to fit the model to yellowfin data using a standard annual recruitment formulation proved unsuccessful. The model could not find a significant growth signal in the size data and the von Bertalanffy parameter $K$ typically converged to zero. While there are clear length modes in the size data and these can be followed in some cases for a year or more, the appearance of modes is somewhat erratic and is certainly not with a consistent annual spacing for all fisheries. This situation is to be expected given that yellowfin spawning does not follow a clear seasonal pattern in the tropics but occurs sporadically when food supplies are plentiful (Itano 2000). To solve this problem, we introduced additional structure into the model to allow multiple recruitments per year. The results presented in this report were derived using four recruitments per year, which are assumed to occur at the start of each quarter.

The distribution of recruitment among the seven model regions was estimated and allowed to vary over time in an unconstrained fashion. The time-series variation in spatially-aggregated recruitment was somewhat constrained by a lognormal prior. The variance of the prior was set such that recruitments of about three times and one third of the average recruitment would occur about once every 20 years on average.

Age and growth

The standard assumptions made concerning age and growth in the MULTIFAN-CL model are (i) the lengths-at-age are assumed to be normally distributed for each age class; (ii) the mean lengths at age are assumed to follow a von Bertalanffy growth curve; (iii) the standard deviations of length for each age class are assumed to be a linear function of the mean length at age. For any specific model, it is necessary to assume the number of significant age-classes in the exploited population, with the last age-class being defined as a “plus group”, i.e. all fish of the designated age and older. This is a common assumption for any age-structured model. For the results presented here, 20 quarterly age classes have been assumed.

Preliminary analyses assuming a standard von Bertalanffy growth pattern indicated that there was substantial departure from the model, particularly for sizes up to about 80 cm. Similar observations have been made on yellowfin growth patterns determined from daily otolith increments and tagging data (Lehodey and Leroy 1999). We therefore modeled growth by allowing the mean lengths of the first eight quarterly age classes to be independent parameters, with the last twelve mean lengths following a von Bertalanffy growth curve.

Selectivity

Selectivity is fishery-specific and was assumed to be time-invariant. Essentially, the model allows random variability in selectivity but time-series trends are assumed to be absent. Selectivity coefficients have a range of 0–1, and for the longline fisheries (which catch mainly adult yellowfin) were assumed to increase with age and to remain at the maximum once attained. Initially, selectivities for all longline fisheries were constrained to be equal. Subsequently, selectivity for the longline fishery in region 1 (fishery 10) was allowed to have independent parameters in order to better fit the length-frequency data for this fishery.

The selectivity coefficients are expressed as age-specific parameters, but were smoothed according to the degree of length overlap between adjacent age classes. This is appropriate where selectivity is thought to be a fundamentally length-based process (Fournier
et al. 1998). The coefficients for the last four age classes, for which the mean lengths are very similar, are constrained to be equal for all fisheries.

**Catchability**

Catchability was allowed to vary slowly over time (akin to a random walk) for all non-longline fisheries using a structural time-series approach, and seasonally for all fisheries apart from the Philippines and Indonesian fisheries (in which the data were based on annual estimates). Random walk steps were taken every three years, with the variance of the catchability deviations was constrained to enhance the stability of the model. The variances were specified for the different fisheries according to our prior belief regarding the extent to which catchability may have changed. For the Philippines and Indonesian fisheries (1–3), no effort estimates were available. We made the minimal assumption that effort for these fisheries was constant over time, but set the catchability deviation variance to be high (equivalent to a coefficient of variation (CV) of about 0.7), thus allowing catchability changes to compensate for failure of this assumption. For the purse seine fisheries, the assumption was equivalent to a CV for the catchability deviations of 0.10. For the longline fisheries, we assumed that catchability varied seasonally, but that its average annual value was both constant over time and among the different regions (fisheries). This assumption seemed reasonable given that the estimation of “effective” fishing effort was designed to remove spatial and temporal variability in CPUE due to targeting changes and variation in the depth of optimal yellowfin habitat. In essence, we allowed longline CPUE constructed using “effective” effort to index yellowfin abundance both among areas and over time.

**Effort variability**

Effort deviations were used to model the random variation in the effort – fishing mortality relationship. The variances of the effort deviations were set for each fishery according to our prior belief regarding how well the effort data indexed fishing mortality (or put another way, how well CPUE observations indexed exploitable abundance). For the Philippines and Indonesian fisheries for which effort data were unavailable, we set the variance at a high level (equivalent to a CV of about 0.7), to allow the effort deviations to account for fluctuations in the catch caused by variation in real effort. For the purse seine fisheries, the variance was set at a moderate level (equivalent to a CV of about 0.20). For the longline fisheries, the variance was set at a low level (equivalent to a CV of about 0.10) to reflect our assumption that longline CPUE (using the effective effort estimates) provides a relatively good index of abundance.

**Natural mortality**

Natural mortality was assumed to be age-specific, but invariant over time and region. Penalties on the first difference, second difference and deviations from the mean were applied to restrict the age-specific variability to a certain extent.

**Movement**

Movement was assumed to be time invariant and to occur instantaneously at the beginning of each quarter. Movement between adjacent regions only was allowed. For age-independent movement, there would be two non-zero transfer coefficients for region boundary of the model, i.e. 18 transfer coefficients. We allowed each of these coefficients to be age-dependent in a simple linear fashion, enabling the rate of movement across each region boundary to increase or decrease linearly with age.

**Initial population**

The population age structure in year 1 in each region is determined as a function of the average total mortality during the first five years in each region. This assumption avoids
having to treat the initial age structure, which is generally poorly determined, as independent parameters in the model.

**Results**

**Fit of the model to the data**

The fit of the model to the total catch data by fishery is very good (Figure 6), which reflects our assumption that observation errors in the total catch estimates are relatively small.

The fit to the length data is displayed in Figure 7 for length samples aggregated over time for each fishery. The fits for the individual length samples disaggregated by time period for each fishery are given in the Appendix. Figure 7 provides a convenient means of assessing the overall fit of the model to the length data for each fishery. On the whole, the model appears to have captured the main features of the data, particularly for the larger, more heavily sampled fisheries. The modal structure evident in the Philippines, Indonesian and some of the purse seine length-frequency data is well represented by the model predictions, while the shape and location of the length distributions of all fisheries is well estimated.

There is more variability in the fits when the data are disaggregated by time period, but on the whole the modal structure of the various samples and modal progression over time seem to be consistently interpreted by the model. A good example of modal progression can be seen in fishery 10 (the longline fishery in region 1) from about sample 96 onwards (see Appendix). The modal structure and progression are very clear in these samples and the model has replicated these features very well.

The fits of the model to the tagging data compiled by calendar time and by time at liberty are shown in Figure 8. The fits appear to be satisfactory. There is some divergence between observed and predicted tag returns for the longer times at liberty, which could be related to constraints on reporting rates among fisheries.

**Age and growth**

Using the four-recruitment-per-year formulation, the model was able to detect a coherent growth signal in the size data. The estimated growth curve is shown in Figure 9. The non-von Bertalanffy growth of juvenile yellowfin is clearly evident, with a pronounced reduction in growth rate in the 40–70 cm size range. This growth pattern is similar to that observed in otolith data, although our model estimates suggest somewhat slower absolute growth rates than those obtained from the otolith data (Figure 10).

A comparison of the estimated growth curve with tagging data can also be made. Figure 11 shows length and age at recapture (estimated from approximate age at release plus time at liberty) of tagged yellowfin tuna at liberty greater than 100 days plotted over the growth curve estimated by model. There is consistency in the pattern of depressed growth in the 40-70 cm size range, although the absolute growth rates of the tagged yellowfin tuna appear to be somewhat slower than predicted by the model.
Figure 6. Observed (circles) and predicted (lines) total catches by time period for each fishery.
Figure 7. Observed (yellow histograms) and predicted (red lines) length-frequency data aggregated over time for each fishery.
Figure 8. Observed (red dots) and predicted (blue lines) tag returns by time period (upper panel) and by periods at liberty (lower panel).
Figure 9. Estimated mean lengths-at-age for yellowfin tuna (thick line). The thin lines are plus and minus 2 standard deviations in length-at-age and are indicative of the estimated length range of each age class.

Figure 10. The estimated yellowfin tuna growth curve (assuming age class 1 is 0.25 years of age) plotted with length-at-age observations based on daily ring counts from otoliths.
Figure 11. The estimated yellowfin tuna growth curve (assuming age class 1 is 0.25 years of age) plotted with length-at-age estimates for recaptured tagged yellowfin tuna. Age-at-recapture was determined by estimating age-at-release from length-at-release using the inverse of the estimated otolith-based growth curve, and adding time at liberty. Only tag returns at liberty for more than 100 days are shown.

Selectivity

Estimated selectivity coefficients are generally consistent with expectation (Figure 12). The Philippines ringnet/purse seine fishery (fishery 1) and the Indonesian fishery (fishery 3) select the smallest fish, while the Philippines handline fishery (fishery 2) is directed towards both small and large yellowfin tuna. Purse seine associated sets (fisheries 4, 6 and 8) select both small fish and large fish, while purse seine unassociated sets (fisheries 5, 7 and 9) have a greater focus on medium to large yellowfin tuna. Longline selectivity coefficients increase to full recruitment at >3 years of age. Recall that the longline selectivities for region 1 (fishery 10) were allowed to differ from those in the other regions in order to provide a better fit to the length-frequency data. This resulted in a slight shift in selectivity towards younger age classes for this region.

Catchability

Estimated catchability trends with effort deviations are shown in Figure 13. Trends for the Philippines and Indonesian fisheries (fisheries 1–3) are increasing over time. This simply reflects the increasing catch of those fisheries and the “null hypothesis” of constant effort where effort data are completely absent for a fishery, i.e. the model uses increasing catchability to explain the increase in catch in these fisheries.

Catchability trends and seasonal variation are generally slight for the purse seine fisheries (fisheries 4–9). One exception to this in fishery 6 (associated sets, region 4), where the catchability increases strongly in the last few years of the analysis. Possibly, this is related to the increased use of drifting FADs in recent years.

For the longline fisheries (catchability assumed to have no time series trends), the effort deviations do not show any obvious trends about the average catchability. Seasonal variation in catchability is apparent in all longline fisheries, but is greater for fisheries 10, 11 (regions 1 and 2 in the north), 15 and 16 (regions 6 and 7 in the south). The phases of the seasonality in the north and south are offset by approximately 0.5 years, as expected (Figure
14). Note that this apparent seasonality could in fact be due to seasonal movement, however this hypothesis has not yet been tested.

Figure 12. Estimated yellowfin tuna selectivity coefficients, by fishery.
Figure 13. Estimated catchability time series (lines) and the catchability plus effort deviations (open circles).
Figure 14. Comparison of seasonal catchability coefficients from longline fisheries in northern (fishery 10 region 1) and southern (fishery 15 region 6) regions.

**Natural mortality**

Natural mortality shows considerable variation with size and age class (Figure 15). For the mid-sizes of ~55-90 cm, the estimates are in the range 0.60-0.70 yr$^{-1}$, which is consistent with values commonly assumed for yellowfin tuna in other areas. The right hand end of the curve begins its upward movement at around the size at first maturity. After about 140 cm in size, $M$ is estimated to decline sharply. One possible interpretation of this is that female yellowfin suffer a high mortality associated with spawning, with aggregate $M$ falling at larger size as females make up a declining proportion of the population (declining incidence of females at large size is suggested in sex ratio samples).

Figure 15. Estimated natural mortality rates (quarterly) and approximate 95% confidence intervals for each age-class plotted against the mean length of each age-class. The red line indicates $M = 0.8$ yr$^{-1}$, a value commonly used in yellowfin stock assessment.
Movement

A representation of the dispersal patterns resulting from the estimated movement parameters is shown in Figure 16, which shows the changes in the relative distributions over time of cohorts originating in each region. Yellowfin tuna in regions 1 and 2 appear to have the strongest “residence”, although this could simply be due to a lack of information in the available data on movement from these regions to counter the weak priors on movement coefficients (zero). Movement is probably better determined in the tropical regions (3, 4 and 5) because the majority of tag releases occurred there. Rapid exchange of fish between regions 4 and 5 is evident. While there is rapid movement of fish from region 3 into regions 4 and 5, the reverse movement is not estimated to occur to any significant extent. This implies that estimated net movement is strongly west to east.

Recruitment

The recruitment estimates display considerable low- and high-frequency variation (Figure 17). The low frequency variation might be correlated with decadal-scale environmental variation and some of the higher frequency variation to the El Nino – La Nina cycle, although these hypotheses have not yet been examined in detail. The high-frequency variation appears to be seasonal, although the pattern is not consistent. The precision of the recruitment estimates is indicated by the approximate coefficients of variation shown in Figure 18. These vary between about 0.1 and 0.3 with a slight declining trend.

There is some evidence of relatively weak recruitment in the last two years of the analysis (1997 and 1998). This coincides with a sharp rise in catchability and effort deviations for some of the purse seine fisheries, particularly in fishery 6 (associated sets, region 4 – see Figure 13). It is possible that these parameters might be highly correlated, and this requires further study.

The average distribution of recruitment among the regions is estimated to be 30% of the total recruitment contributed by region 3, 46% by region 4, 18% by region 5, with the remaining 6% contributed by the subtropical regions. This estimated average distribution is consistent with general biological understanding of yellowfin spawning and recruitment in the WCPO.

Estimates of recruitment are plotted against adult biomass estimates lagged by one quarter for regions 3, 4, 5 and for the total stock in Figure 19. There is little evidence of a relationship between adult biomass and recruitment.
Figure 16. A representation of the estimated movement coefficients for yellowfin tuna. In each panel, the estimated relative distribution (by region) of a cohort of 1000 recruits originating in a specific region is plotted by quarter. Movement from region 1 was estimated to be zero and is not shown.
Figure 17. Estimated quarterly recruitment with a four-quarter moving average (thicker line).

Figure 18. Approximate coefficients of variation for the recruitment estimates.
Figure 19. Estimated recruitment plotted against estimated adult biomass for regions 3, 4, 5, and the total model area.

Biomass trends

Time series of total and adult biomass, by region are shown in Figure 20. Most of the biomass is estimated to occur in the tropical regions 3, 4 and 5. Biomass peaked in the early 1980s and has been trending downwards since that time. The decline in the past few years has been particularly rapid. The average biomass for 1998 is estimated to be about 50% of the average biomass for the first three years of the time series. The biomass of adult yellowfin tuna (assumed to be 50% of age classes 7 and 8 (approximately 2.5–3.0 years of age) and 100% of older age classes) shows similar trends and spatial distribution to the total biomass. The average adult biomass in 1998 is about 60% of that during the early years of the time series.

Fishing mortality

Quarterly fishing mortality rates for annual age groups are shown in Figure 21 for the total model area and individual model regions. Fishing mortality increased strongly in recent years for age 1 yellowfin. This increase was concentrated mostly in regions 3 and 4. Fishing mortality rates for other age groups also increased strongly in region 4. Even with these recent increases, fishing mortality is still considerably less than natural mortality and would not be regarded as overfishing under most definitions.
Figure 20. Time series of estimated total (upper panel) and adult (lower panel) biomass by region.
Figure 21. Estimates of quarterly fishing mortality by annual age groups by region and for the total model area.

The fishing mortality estimates are conditioned to some extent on the estimates of tag-reporting rates. Fortunately, we had independent estimates of tag reporting for some fisheries (purse seine), which were incorporated into this analysis as priors. The model estimates of tag-reporting rates follow the priors for these fisheries, but vary considerably for the other fisheries according to the model data. The tag-reporting rate estimates are shown in Figure 22.
Conclusions

The yellowfin tuna model has integrated catch, effort, length-frequency and tagging data into a coherent analysis that is broadly consistent with other information on the biology and fisheries. The major conclusions of the analysis to date are:

1. The growth estimates are consistent with estimates from otolith analysis and are in general agreement with length-increment data from tagged yellowfin.
2. Estimates of natural mortality are strongly age-specific, with higher rates estimated for young yellowfin and for fish approaching maturity. The basal rate is similar to values commonly used in yellowfin assessments in other regions.
3. Recruitment shows considerable variation at several different time scales. Recruitment is estimated to have been relatively low during the last two years of the analysis.
4. The main feature of both the total and adult biomass estimates is a strong decline in the past 2–3 years. These declines would appear to be driven by the lower recruitments that have occurred in recent years.
5. Fishing mortality has increased strongly in recent years, particularly for age 1 yellowfin and particularly in regions 3 and 4. These increases are obviously related to the decline in recruitment (in the sense that in combination they will maintain catches at much the same level). They may also be related to the increased use of FADs which may have increased the vulnerability of small yellowfin.
6. While fishing mortality has increased recently, the estimates obtained in this analysis would not be classified as overfishing under most currently used definitions.

References


