Stock assessment of skipjack tuna in the western and central Pacific Ocean

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1 Background

1.1 Biology

Surface-schooling, adult skipjack tuna (>40 cm fork length, FL) are commonly found in tropical and subtropical waters of the Pacific Ocean. Skipjack in the western and central Pacific Ocean (WCPO) are considered a single stock for assessment purposes (Wild and Hampton 1994). In the western Pacific, warm, poleward-flowing currents near northern Japan and southern Australia extend their distribution to 40°N and 40°S. These limits roughly correspond to the 20°C surface isotherm. A substantial amount of information on skipjack movement is available from tagging programmes (Figure 1). In general, skipjack movement is highly variable (Sibert et al. 1999) but is thought to be influenced by large-scale oceanographic variability (Lehodey et al. 1997).

Skipjack growth is rapid compared to yellowfin and bigeye tuna. In the Pacific, approximate age estimates from tagging and otoliths indicate FLs of 45, 64, 75, and 80 cm for ages 1–4; though significant differences occur between individuals. The longest period at liberty for a tagged skipjack was 4.5 years. Estimates of natural mortality rate have been obtained using a size-structured tag attrition model (Hampton 2000), which indicated that natural mortality was substantially larger for small skipjack (21–30 cm FL, $M=0.8$ mo$^{-1}$) than larger skipjack (51–70 cm FL, $M=0.12–0.15$ mo$^{-1}$).

1.2 Fisheries

Skipjack tuna fisheries can be classified into the Japan distant-water and offshore pole-and-line fleets, domestic pole-and-line fleets based in island countries, artisanal fleets based in the Philippines, eastern Indonesia and the Pacific Islands, and distant-water and Pacific-Island-based purse seine fleets. The Japanese distant-water and offshore pole-and-line fleets operate over a large region in the WCPO (Figure 2a). A domestic pole-and-line fishery occurred in PNG from 1970 to 1985 and an active fishery has occurred in Fiji and the Solomon Islands since 1974 and 1971, respectively (Fig. 2b). A variety of gear types (e.g. gillnet, hook and line, longline, purse seine, ring net, pole-and-line and unclassified) capture skipjack in the Philippines and Indonesia (Figure 2c). Small but locally important artisanal fisheries for skipjack and other tuna (using mainly trolling and traditional methods) also occur in many of the Pacific Islands. Purse seine fleets usually operate in equatorial waters from 10°N to 10°S (Figure 2d-f), although a Japan offshore purse seine fleet operates in the sub-tropical North Pacific. The distant-water fleets from Japan, Korea, Taiwan and the USA capture most of the skipjack in the WCPO. Since 1975, purse seiners flagged in various countries (e.g. Australia, Federated States of Micronesia, Kiribati, Mexico, Papua New Guinea, Russia, Solomon Islands, and Vanuatu) have operated in the WCPO. The purse seine fishery is usually classified by set type categories – log, fish aggregation device (FAD) and school sets – because the different set types have somewhat different spatial distributions, catch per unit effort (CPUE) and catch different sizes of skipjack and other tuna. The combined distribution of skipjack catch by these fleets shows tropical (mainly purse seine) and subtropical (Japan-based pole-and-line and purse seine) components (Figure 3).

Skipjack tuna catches in the WCPO have increased steadily since 1970, more than doubling during the 1980s. The catch has been relatively stable during the 1990s (range 800,000–1,300,000 mt), with catches of more than a million metric tonnes occurring in 1991, 1992, 1995, and each year since 1998 (Figure 4). Pole-and-line fleets, primarily Japanese, initially dominated the fishery, with the catch peaking at 380,000 mt in 1984, but the relative importance of this fishery has declined steadily for economic reasons. Skipjack tuna catch increased during the 1980s due to growth in the international purse-seine fleet, combined with increased catches by domestic fleets from the Philippines and Indonesia (which have made up to 20–25% of the total skipjack tuna catch in WCPO in recent years).
2 Data compilation

Data used in the MULTIFAN-CL skipjack assessment consist of catch, effort and length-frequency data for the fisheries defined in the analysis and tag-recapture data. The details of these data and their stratification are described below.

2.1 Spatial stratification

The geographical area considered in the assessment corresponds to the western and central Pacific Ocean from 45°N to 20°S and from oceanic waters adjacent to the east Asian coast to 150°W (Figure 3). The assessment model area contains six spatial regions (Figure 3) as used in a previous skipjack CPUE standardization study (Ogura and Shono 1999) and enlarged to include the domestic fisheries of the Philippines and eastern Indonesia. The assessment area now covers practically the entire skipjack fishery in the WCPO, with the exception of relatively minor catches south of 20°S.

2.2 Temporal stratification

The time period covered by the assessment is 1972–2001. Within this period, data were compiled into quarters (Jan–Mar, Apr–Jun, Jul–Sep, Oct–Dec).

2.3 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. For most pelagic fisheries assessments, fisheries defined according to gear type, fishing method and region will usually suffice.

For this analysis, pole-and-line fishing activity was stratified by national fleet and region. The Japanese pole-and-line fleet was further stratified by distant-water and offshore categories because of the different operational characteristics of these component fleets. Purse seine fishing activity was aggregated over all nationalities, but stratified by region and three set types (log, FAD and school sets) in order to sufficiently capture the variability in fishing operations. Data on skipjack catches from a long history of Japanese research longline cruises in the WCPO were also available for this analysis; therefore, a research longline fishery was defined to allow the incorporation of these data. Finally, domestic fishery categories for the Philippines and Indonesia were also included in the fishery definitions. Overall, 24 fisheries were defined in the analysis (Table 1).

2.4 Catch and effort data

Catch and effort data were compiled according to the fisheries defined above and the six-region, quarterly stratification. The catches of all fisheries, with the exception of the research longline fishery, were expressed in weight of fish. Research longline catches were expressed in numbers of fish. In all cases, catches were raised, as appropriate, to represent the total retained catches by area/time strata. Discarded catches were not included in the analysis.

For the Japanese pole-and-line fisheries, standardised effort time-series were estimated using General Linear Model (GLM) analyses (Ogura and Shono 1999). Separate analyses were conducted for the distant-water and offshore fleets. The factors included in the analyses were year, quarter, region, effect of refrigerated bait tank use, effect of bird radar use, effect of sonar use, effect of satellite imagery use and albacore CPUE. Nominal fishing vessel days was used as the effort measurement for all other pole-and-line and purse seine fisheries. For the purse seine fisheries, vessel days were apportioned to the three set types using the proportions of total sets in the various region/time strata attributed to the three set types. Effort data were not available for the Philippines domestic, Indonesia domestic and research longline fisheries (these vessels were targeting other tuna
species) – effort was declared as “missing” for these fisheries. CPUE plots for each fishery are shown in Figure 5.

2.5 Length-frequency data

Available length-frequency data for each of the defined fisheries were compiled into 54 2-cm size classes (2–4 cm to 108–110 cm). Length-frequency observations consisted of the actual number of skipjack measured.

Some fisheries have not been consistently sampled at the same levels over time. Also, it was not possible to discriminate samples for the Japanese offshore and distant-water fleets in regions 1, 2 and 4. The samples were therefore arbitrarily assigned to the offshore fleets in each region, but the selectivity coefficients for these fisheries were grouped so that they were, in effect, estimated from the same length-frequency data.

2.6 Tagging data

A large amount of tagging data was available for incorporation into the MULTIFAN-CL analysis. The data used consisted of the OFP’s Skipjack Survey and Assessment Project (SSAP) carried out during 1977–80, the Regional Tuna Tagging Project (RTTP) during 1989–92 and in-country projects in the Solomon Islands (1989–90), Kiribati (1991), Fiji (1992) and the Philippines (1992). Also, tagging data from regular Japanese research cruises were available for the period 1988–2001. Only Japanese tags released north of 15°N, an area not well covered by the SPC experiments, were used in the analysis. Japanese tag releases south of 15°N were not used because of suspected atypical tag reporting rates of these tags compared to the SPC tags.

Tags were released using standard tuna tagging equipment and techniques by trained scientists and scientific observers. Tags have been returned mostly from purse seine vessels and processing and unloading facilities throughout the Asia-Pacific region.

For incorporation into the MULTIFAN-CL analysis, tag releases were stratified by release region, time period of release (quarter) and the same size classes used to stratify the length-frequency data. A total of 219,809 releases were classified into 145 tag release groups. The returns from each size-class of each tag release group (17,251 tag returns in total) were then classified by recapture fishery and recapture time period (quarter). Because tag returns by purse seiners were often not accompanied by information concerning the set type, tag return data were aggregated across set types for the purse seine fisheries in each region. The population dynamics model was in turn configured to predict equivalent estimated tag recaptures by these grouped fisheries.

3 Structural assumptions of the model

As with any model, various structural assumptions have been made in the skipjack 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 Hampton and Fournier (2001a). The main structural assumptions used in the skipjack model are discussed below and are summarised in Table 2.

3.1 Observation models for the data

There are three data components that contribute to the log-likelihood function – the total catch data, the length-frequency data and the tagging data. The observed total catch data are assumed to be unbiased and relatively precise, with the SD of residuals on the log scale being 0.07.

The probability distributions for the length-frequency proportions are assumed to be approximated by robust normal distributions, with the variance determined by the sample size and the observed proportion. The effective sample size is assumed to be 0.1 times the actual sample size,
limited to a maximum of 1000. This assumption recognises that length-frequency samples are not truly random and that even very large samples (>1000) taken from a particular fishery in a quarter would have a variance equivalent to a random sample of 100 fish.

A log-likelihood component for the tag data was computed using a negative binomial distribution in which fishery-specific variance parameters were estimated from the data. The negative binomial is preferred over the more commonly used Poisson distribution because tagging data often exhibit more variability than can be attributed by the Poisson. We have employed a parameterization of the variance parameters such that as they approach infinity, the negative binomial approaches the Poisson. Therefore, if the tag return data show high variability (for example, due to contagion or non-independence of tags), then the negative binomial is able to recognise this. This would then provide a more realistic weighting of the tag return data in the overall log-likelihood and allow the variability to impact the confidence intervals of estimated parameters. A complete derivation and description of the negative binomial likelihood function for tagging data is provided in Hampton and Fournier (2001a) (Appendix C).

3.2 Tag reporting

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 various Japanese pole-and-line 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. All reporting rates were assumed to be stable over time.

3.3 Tag mixing

We assume that tagged skipjack gradually mix with the untagged population at the region level and that this mixing process is complete by the second quarter after release.

3.4 Recruitment

“Recruitment” in terms of the MULTIFAN-CL model is the appearance of age-class 1 fish in the population. The results presented in this report were derived using four recruitments per year, which are assumed to occur at the start of each quarter. This is used as an approximation to continuous recruitment.

The distribution of recruitment among the six 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 25 years on average.

Spatially-aggregated recruitment was assumed to have a weak relationship with the parental biomass via a Beverton and Holt stock-recruitment relationship (SRR). The SRR was incorporated mainly so that a yield analysis could be undertaken for stock assessment purposes. We therefore opted to apply a relatively weak penalty for deviation from the SRR so that it would have only a slight effect on the recruitment and other model estimates (see Hampton and Fournier 2001a, Appendix D).

Typically, fisheries data are very uninformative about SRR parameters and it is generally necessary to constrain the parameterisation in order to have stable model behaviour. We have incorporated a beta-distributed prior on the “steepness” ($S$) of the SRR, with $S$ defined as the ratio of the equilibrium recruitment produced by 20% of the equilibrium unexploited spawning biomass to that produced by the equilibrium unexploited spawning biomass (Francis 1992; Maunder and Watters 2001). A formal derivation of the SRR parameterization and the contribution of the steepness prior to
the log-likelihood is given in Hampton and Fournier (2001b). The prior was specified by mode = 0.9 and SD = 0.04 (beta parameters $a = 46$, $b = 6$). In other words, our prior belief is that the reduction in equilibrium recruitment when the equilibrium spawning biomass is reduced to 20% of its unexploited level would be fairly small (a decline of 10%).

3.5 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, 16 quarterly age-classes have been assumed.

Length-based assessments of other tuna species have indicated that there is substantial departure from the von Bertalanffy model, particularly for juvenile age-classes. To allow for this possibility in skipjack tuna, we allowed the mean lengths of the first six quarterly age-classes to be independent parameters, with the last ten mean lengths following a von Bertalanffy growth curve.

3.6 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 research longline fisheries were assumed to increase with age and to remain at the maximum once attained. Selectivities for all Japanese pole-and-line fisheries were constrained to be equal. Selectivities for all other fisheries were independently estimated. 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 two age-classes, for which the mean lengths are very similar, are constrained to be equal for all fisheries.

3.7 Catchability

Catchability was allowed to vary slowly over time (akin to a random walk) for all fisheries. Random walk steps were taken every two years, and the deviations were constrained by a prior distribution of mean zero and CV (on the log scale) of 0.1. However, for the Philippines, Indonesian and research longline fisheries, no reliable effort estimates were available. We made the assumption that effort for these fisheries was constant over time, but set the variance of the priors to be high (equivalent to a CV of about 0.7 on the log scale), thus allowing catchability changes to compensate for failure of this assumption.

Various schemes for assigning common catchability patterns among fisheries were tested. In particular, we felt that it might be appropriate for the Japanese distant-water pole-and-line fisheries and the Japanese offshore pole-and-line fisheries to have common catchability among the different regions in which those fleets operate because of the way in which the effort data were pre-standardized using the GLM analyses. However, such grouping of parameters resulted in distributions of effort deviations (or residuals) that showed time-series trends and/or uneven distributions about zero, indicating that the assumptions regarding common catchability were not valid. Therefore, the results reported here are from a model in which catchability parameters are independently estimated for each fishery.
3.8 Effort variability

Effort deviations, constrained by prior distributions of zero mean, were used to model the random variation in the effort – fishing mortality relationship. For the Philippines, Indonesian and research longline fisheries for which reliable effort data were unavailable, we set the prior variance at a high level (equivalent to a CV of about 0.7 on the log scale), to allow the effort deviations to account for fluctuations in the catch caused by variation in real effort. For all other fisheries, the variance was set at a moderate level (equivalent to a CV of about 0.2 on the log scale).

3.9 Movement

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

3.10 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.

3.11 Initial population

The population age structure in the initial time period in each region is determined as a function of the average total mortality during the first 20 quarters and the average recruitment in quarters 2–20 in each region. This assumption avoids having to treat the initial age structure, which is generally poorly determined, as independent parameters in the model.

4 Results

4.1 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. 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 pole-and-line and purse seine length-frequency data is represented by the model predictions. The modal structure in the domestic fishery of Indonesia and the PNG pole-and-line fishery is not as well represented as the other fisheries in the model, probably due to the small size of available length samples and limited temporal coverage for these fisheries. 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.

The fits of the model to the tagging data compiled by calendar time and by time at liberty are shown in the upper portion of Figure 8. These aggregated fits appear to be very good, with little divergence between observed and predicted tag returns. However, some discrepancies are evident when the observed and predicted data are broken down by fishery groups (lower portion of Figure 8). These discrepancies occur mainly in the Japanese pole-and-line fisheries. For these fisheries, there were periods when few tags were observed despite considerable numbers being predicted (e.g. JPDW PL 3) and vice versa (e.g. JPOS PL 1 and JPOS PL 2). This may indicate that the assumption concerning temporal stability of tag-reporting rates was not appropriate for these fisheries. For the
remaining fisheries that returned considerable numbers of tags, the match between observed and predicted returns is generally good.

4.2 Tag reporting rates

There is considerable variation among fisheries in estimated tag-reporting rates (Figure 9). Very low reporting rates are estimated for several Japanese offshore and distant-water pole-and-line fisheries. This was not simply due to an inability of the model to estimate reporting rates. If this were the case, the estimates would have remained near the mode of their priors – 0.5 (SD=0.22) in each case. For the remaining fisheries, the estimates were generally close to the modes of the priors.

4.3 Age and growth

Using the four-recruitment-per-year formulation, the model was able to detect a reasonably coherent growth signal in the size data. The estimated growth curve is shown in Figure 10a. The variation in length-at-age is constant across age-classes. This is surprising, as we would expect the variation to increase with increasing age. Possibly, there was insufficient information in the data to provide a signal for changes in the variation in length-at-age.

A comparison of the estimated growth curve and tag-recapture observations (not used to estimate growth parameters in this model) is shown in Figure 10b. Correspondence is good for the smaller fish, however the older tagged fish have somewhat smaller lengths that would be predicted by the MULTIFAN-CL growth model. One explanation for this could be that the surface gears (purse seine and pole-and-line) catch primarily smaller skipjack <60 cm FL, and that the older skipjack captured by these gears tend to be the smaller and slower growing members of those age-classes. If such a phenomenon were occurring, the use of a model with purely size-based rather than age-based selectivity would be more appropriate.

4.4 Selectivity

Estimated selectivity coefficients are generally consistent with expectation (Figure 11). The PH DOM 5 and ID DOM 5 fisheries select the smallest fish. Pole-and-line and purse seine fisheries begin to select fish at 3 or 4 quarters of age. Most of the purse seine and pole-and-line fisheries have a bimodal appearance, with high selectivity for age-classes 5−7 and for the oldest 3 or 4 age-classes. Only the longline fisheries have been assumed to have a monotonically increasing selectivity with age.

4.5 Catchability

Estimated catchability trends are shown in Figure 12. Seasonal variability is strong for many of the pole-and-line fisheries, particularly for the Japanese fleets in regions 1−4. Time-series trends are also evident for many of the fisheries. Of particular note are the decreasing trends of most of the Japanese pole-and-line fisheries since around 1980 and the increases in catchability for several of the purse seine fisheries.

4.6 Effort deviations

Time-series plots of effort deviations are useful to see if the catchability assumptions employed are appropriate, i.e. they result in even distributions of effort deviations about zero and no time-series trends. The effort deviation plots for the skipjack model display these characteristics (Figure 13). Earlier model runs employing more restrictive assumptions on catchability, e.g. all JPOS PL and JPDW PL catchability constant over time and shared among regions, produced patterns of effort deviations that indicated the inappropriateness of those assumptions. The assumptions ultimately used in the analysis, i.e. all fisheries have independent catchability with time-series trends, were required to eliminate such patterns.
4.7 Natural mortality

Natural mortality shows a classical U-shaped relationship with age (Figure 14). Mortality is lowest (~1.5 yr\(^{-1}\)) for age-classes 6–9 (a size of 52–68 cm). The 95% confidence intervals are also the lowest for these age-classes. Mortality is highest (~3.0 yr\(^{-1}\)) in the initial 4 (< 45 cm) and last 5 (>75 cm) age-classes.

4.8 Movement

A representation of the dispersal pattern resulting from the estimated movement parameters is shown in Figure 15. This figure shows the changes in the relative distributions over time of cohorts originating in each region.

It is also possible to use the movement coefficients, the average proportions of the total recruitment occurring in each region and the age-specific natural mortality rates to estimate the equilibrium stock composition in each region in the absence of fishing (Figure 16). The model results imply that relatively high percentages (>90% for regions 1–3, 82% for region 4, 75% for region 5 and 67% for region 6) of the equilibrium biomass each region is composed of fish recruited in that region. These generally high percentages might be considered surprising in view of skipjack’s general classification as “highly migratory”. However, the pattern observed here is consistent with recent analyses of skipjack tuna tagging data (Sibert and Hampton submitted).

4.9 Recruitment

Time-series of recruitment are shown in Figure 17. Overall recruitment has been higher since the mid-1980s. This might be related to the high frequency of El Niño events, which are thought to enhance skipjack recruitment, since that time. Recruitment was at a record high in 1997–1998, corresponding to the very strong El Niño that occurred then. For the recruitment time-series by region, these patterns were more evident in the tropical regions (4–6) than the sub-tropical regions (1–3).

4.10 Biomass

Time series of biomass by region are shown in Figure 18. The majority of the population occurs in regions 5 and 6. Biomass increased firstly in the mid-1980s in response to the increase in recruitment and surged again in the late 1990s after the strong recruitment in 1997–1998.

4.11 Fishing mortality and the impact of fishing

Annual average fishing mortality rates for juvenile and adult age-classes are shown in Figure 19 for the total model area. Fishing mortality is lower for the juvenile skipjack and has increased continually over time for both age groups since the beginning of the analysis until about 1997. Since 1997, there has been a reduction in fishing mortality that is coincident with the increase in stock biomass.

For a complex model such as this, it is difficult to readily interpret fishing mortality rates and other parameters to obtain a clear picture of the estimated impact of fishing on the stock. To facilitate this, we have computed total biomass trajectories for the population in each region using the estimated recruitment, natural mortality and movement parameters, but assuming that the fishing mortality was zero throughout the time series. Comparison of these biomass trajectories with those incorporating the actual levels of observed historical fishing provides a concise, integrated picture of the impacts of the total fishery on the stock. Biomass trajectories for each region and for the WCPO in total are shown in the left panels of Figure 20. The impact of fishing is significant only in regions 2, 5 and 6. For the WCPO as a whole, the difference between fished and unfished biomass has generally been in the range of 10–15% in recent years and has been fairly stable during the 1990s.
4.12 Yield and reference point analysis

The use of reference points provides a framework for quantitatively determining the status of the stock and its exploitation level. Two types of reference points are often now required for fisheries management: the fishing mortality at maximum sustainable yield (F_{MSY}) is used as an indicator of overfishing; and the biomass at MSY (B_{MSY}) is used as an indicator of an overfished state. It is possible for overfishing to be occurring, but for the stock to not yet be in an overfished state. Conversely, it is possible for the stock to be in an overfished state but for the current level of fishing to be within the overfishing reference point. In this case, the stock has presumably been depressed by past overfishing and would recover to a non-overfished state if the current level of fishing was maintained. It is likely that these reference points, or something similar, will be used for stock status determinations in the new WCPO tuna commission. We have therefore developed a reference point analysis within the MULTIFAN-CL model framework as an example of how this might be applied in WCPO tuna fisheries.

The reference point analysis has been carried out as follows:

1. Estimate population model parameters, including the parameters of a Beverton and Holt stock-recruitment relationship (SRR).
2. Estimate a “base” age-specific fishing mortality vector, \( F_{age} \), various multiples of which are assumed to maintained into the future; for the skipjack tuna assessment, the average \( F_{age} \) over 1997–2001 was used.
3. For various multiples of \( F_{age} \) compute the equilibrium population-at-age, and equilibrium yield using the estimated SRR, natural mortality and other parameters.
4. Compute the equilibrium total biomass, equilibrium adult biomass and equilibrium fishing mortality (averaged over age classes) at MSY. These equilibrium quantities are the reference points.
5. Compare the actual estimated biomass and fishing mortality levels at time \( t \) with these reference points. This is done by computing the ratios \( B_{\text{total}} / B_{\text{MSY}} \), \( B_{\text{adult}} / B_{\text{MSY}} \), \( F_{t} / F_{\text{MSY}} \) and their 95% confidence intervals and comparing them with 1.0. Values of \( F_{t} / F_{\text{MSY}} \) significantly greater than 1.0 would indicate overfishing, while values of \( B_{t} / B_{\text{MSY}} \) and/or \( B_{\text{adult}} / B_{\text{MSY}} \) or less than 1.0 would indicate an overfished state.

Note that these somewhat simplistic notions make assumptions about equilibrium behaviour of the populations. This aspect of reference points and in particular those based on equilibrium models has been roundly criticised (with some justification) in some fisheries circles. One criticism is that long-term changes in recruitment might occur through environmental or ecosystem changes that have little or nothing to do with the fisheries. More generally, it is not unreasonable to view many fish populations as being in a continual state of flux with an equilibrium condition never being reached or maintained for any length of time. In reality, therefore, MSY, F_{MSY} and B_{MSY} are “moving targets” and not static quantities. At best, they should be considered as averages over time, and additional analyses undertaken in cases where it is suspected that important non-fishery-induced changes in productivity may have occurred.

The estimated SRR used in the yield and reference point analyses for skipjack tuna is shown in Figure 21. The scatter of recruitment-biomass points is fairly typical of most fisheries data sets − there is very little information on how recruitment might respond to very low biomass levels. For this reason, it is necessary to constrain the behaviour of the curve in the region towards the origin by the prior assumption for “steepness”. To recap, the assumption was that significant (>10%) recruitment decline occurs only at adult biomass of <20% of virgin levels, i.e. that average recruitment is quite robust to adult biomass decline.

The estimated equilibrium yield using a base \( F_{-}\text{at-age} \) given by the 1997–2001 average is shown in Figure 22. This analysis indicates that, for this average \( F_{-}\text{at-age} \) (i.e. a fishing mortality multiplier of 1.0), the equilibrium yield is approximately 740,000 t per year. This is considerably
lower than the actual catches that occurred during 1997–2001, which averaged about 1.1 million t per year. This is because the yield analysis is based on an equilibrium model in which equilibrium recruitment is predicted on the basis of the SRR shown in Figure 21. However, recruitment during the late 1990s was at a relatively high level which enabled the recent high catches to occur. To demonstrate this effect, we repeated the yield analysis using the estimated average levels of recruitment for 1972–1984 (low-recruitment period) and 1985–2001 (high-recruitment period) instead of using a single SRR. These results are shown in Figure 23. For the high-recruitment period, the yield at an F-multiplier of 1.0 is 950,000 t, which is close to the 1997–2001 average catch. However, if recruitment were to return to pre-1981 levels, the yield at the base $F$-at-age would then be only about 620,000 t.

The maximum equilibrium yield (equivalent to MSY) according to Figure 22 is about 2.7 million t, and is achieved at a F-multiplier of >20. The portion of the yield curve near the current level of $F$-at-age is close to linear. Therefore, in the absence of a technological or economic revolution in the skipjack fishery resulting in order-of-magnitude increases in fishing mortality, it might reasonably be expected that catch, on average, would continue to change almost proportionally with fishing effort over any realistic range that might be contemplated for the foreseeable future. Recruitment variability, influenced by environmental conditions, will continue to be the primary influence on stock size and fishery performance.

The ratios of $F_t/F_{MSY}$ and $B_{adult}^{MSY}/B_{adult}$ are shown in Figure 24, confirming the expected result that skipjack in the WCPO are not currently being overfished, nor is the stock in an overfished state.

5 Conclusions

The major conclusions of the skipjack assessment are as follows:

1. The growth estimates are in general agreement with perceived length-at-age estimates of skipjack from the Pacific and other regions. Moreover, the model seemed to be able to make a consistent interpretation of the size data, which is crucial to a length-based approach. Discrepancies between the estimated growth curve and age-length observations for tagged skipjack might be due to the tropical surface fisheries selecting mainly the smaller, slower growing skipjack from the older age-classes. If this is true, a model incorporating size-based selectivity might be more appropriate. This is an area for further research.

2. Similar to other tropical tunas, estimates of natural mortality are strongly age-specific, with higher rates estimated for younger and older skipjack.

3. While tagging data show that individual skipjack are capable of undertaking long-distance movements of several thousand kilometers, the population-level estimates of dispersal obtained from this model are in fact consistent with some degree of regional fidelity. The contribution of local recruitment to the regional sub-populations is generally 70% or greater.

4. Recruitment showed an upward shift in the mid-1980s and has been at a high level since that time. Particularly high recruitment occurred in 1997–1998. The strong El Niño at around that time and the high frequency of such events during the 1990s is suspected to have had a positive effect on skipjack recruitment. The possible mechanisms involved in this relationship is an area of further research.

5. The biomass trends are driven largely by recruitment, with the highest biomass estimates for the model period being those in 1998–2000. The model results suggest that the skipjack population in the WCPO in recent years has been at an all-time (over the past 30 years) high.

6. Fishing mortality has increased throughout most of the time-series, falling to some extent in recent years. The impact of fishing is relatively slight throughout the model domain.
7. An equilibrium yield analysis confirms that skipjack is currently exploited at a modest level relative to its biological potential. Furthermore, the estimates of $F_t/F_{MSY}$ and $B_{t\text{adult}}/B_{MSY\text{adult}}$ suggest that the stock is neither being overfished nor in an overfished state. Recruitment variability, influenced by environmental conditions, will continue to be the primary influence on stock size and fishery performance.

8. Recommended research and monitoring required to improve the skipjack tuna assessment include the following:

- Continued monitoring and improvement in fisheries statistics is required. In particular, better data generally are required for the Philippines and Indonesian fisheries.
- New conventional tagging experiments, undertaken regularly, would provide additional information on recent levels of fishing mortality, refine estimates of natural mortality and possibly allow some time-series behaviour in movement to be incorporated into the model.
- Further research on environmental influences on skipjack tuna recruitment and movement are required. Environmental time series identified by such research could be incorporated into the MULTIFAN-CL model.

6 Acknowledgements

We are grateful to Miki Ogura of the Japan National Research Institute of Far Seas Fisheries, who compiled the catch, effort and length frequency data for the Japanese pole-and-line and offshore purse seine fisheries and the large amount of tag release and recapture data from Japanese tagging programmes.

7 References


Meeting of the Standing Committee on Tuna and Billfish, 16–23 June 1999, Papeete, French Polynesia.


Table 1. Definition of fisheries for the MULTIFAN-CL skipjack analysis. Gears: PL = pole-and-line; PS = purse seine unspecified set type; PS/LOG = purse seine log set; PS/FAD = purse seine FAD set; PS/SCH = purse seine school set; LL = longline; DOM = the range of artisanal gear types operating in the domestic fisheries of Philippines and Indonesia. Flag/fleets: JP/OS = Japan offshore fleet; JP/DW = Japan distant-water fleet; JP/RES = Japan research/training vessel fleet; PG = Papua New Guinea; SB = Solomon Islands; PH = Philippines; ID = Indonesia; FJ = Fiji; ALL = all nationalities.

<table>
<thead>
<tr>
<th>Fishery code</th>
<th>Gear</th>
<th>Flag/fleet</th>
<th>Region</th>
<th>Fishery code</th>
<th>Gear</th>
<th>Flag</th>
<th>Region</th>
</tr>
</thead>
<tbody>
<tr>
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<td>PL</td>
<td>JP/OS</td>
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<td>PS LOG 5</td>
<td>PS/LOG</td>
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<td>5</td>
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<tr>
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<td>JP/DW</td>
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<td>PS FAD 5</td>
<td>PS/FAD</td>
<td>ALL</td>
<td>5</td>
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<td>PS SCH 5</td>
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<td>ID DOM 5</td>
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<td>JP/DW</td>
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<td>FJ PL 6</td>
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<td>LL</td>
<td>JP/RES</td>
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<td>PS LOG 6</td>
<td>PS/LOG</td>
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<td>PL</td>
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<td>PS/FAD</td>
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<tr>
<td>PG PL 5</td>
<td>PL</td>
<td>PG</td>
<td>5</td>
<td>PS SCH 6</td>
<td>PS/SCH</td>
<td>ALL</td>
<td>6</td>
</tr>
<tr>
<td>SB PL 5</td>
<td>PL</td>
<td>SB</td>
<td>5</td>
<td>JP LL 6</td>
<td>LL</td>
<td>JP/RES</td>
<td>6</td>
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</table>
### Table 2. Main structural assumptions used in the model.

<table>
<thead>
<tr>
<th>Category</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observation model for total catch data</td>
<td>Observation errors small, equivalent to a residual SD on the log scale of 0.07.</td>
</tr>
<tr>
<td>Observation model for length-frequency data</td>
<td>Normal probability distribution of frequencies with variance determined by sample size and observed frequency. Effective sample size is assumed to be 0.1 times actual sample size with a maximum effective sample size of 100.</td>
</tr>
<tr>
<td>Observation model for tagging data</td>
<td>Tag numbers in a stratum have negative binomial probability distribution, with fishery-specific variance parameter.</td>
</tr>
<tr>
<td>Tag reporting</td>
<td>Informative priors for purse seine fisheries (based on tag seeding), moderately informative priors for Philippines and Indonesian fisheries, relatively uninformative priors for all other fisheries. All reporting rates constant over time.</td>
</tr>
<tr>
<td>Tag mixing</td>
<td>Tags assumed to be randomly mixed at the model region level from the quarter following the quarter of release.</td>
</tr>
<tr>
<td>Recruitment</td>
<td>Occurs as discrete events at the start of each quarter. Spatially-aggregated recruitment is weakly related to spawning biomass in the prior quarter via a Beverton-Holt SRR (beta prior for steepness with mode at 0.9 and SD of 0.04). The spatial distribution of recruitment in each quarter is allowed to vary in an unconstrained fashion.</td>
</tr>
<tr>
<td>Initial population</td>
<td>Is a function of the equilibrium age structure in each region, which is assumed to arise from the total mortality and movement rates estimated for the initial 20 quarters of the analysis.</td>
</tr>
<tr>
<td>Age and growth</td>
<td>16 quarterly age-classes, with the last representing a plus group. Juvenile age-classes 1–6 have independent mean lengths; adult age-class mean lengths constrained by von Bertalanffy growth curve. Mean weights ($W_j$) computed internally by estimating the distribution of weight-at-age from the distribution of length-at-age and applying the weight-length relationship $W = aL^b$ ($a=0.8.6388e-06$, $b=3.2174$ estimated from available length-weight data).</td>
</tr>
<tr>
<td>Selectivity</td>
<td>Constant over time. Various smoothing penalties applied. Coefficients for the last 2 age-classes are constrained to be equal. All Japan pole-and-line fisheries share common parameters. Research longline selectivities are non-decreasing with increasing age.</td>
</tr>
<tr>
<td>Catchability</td>
<td>JPDW PL fleets have common catchability. Likewise, JPOS PL fleets with the exception of JPOS PL 4 have common catchability. Seasonal variation for all fisheries apart from Philippines and Indonesian fisheries. All fisheries have structural time-series variation, with random steps (catchability deviations) taken every 2 years. Catchability deviations constrained by a prior distribution with (on the log scale) mean 0 and SD 0.1 (SD is 0.7 for Philippines, Indonesian and research longline fisheries with missing effort data).</td>
</tr>
<tr>
<td>Fishing effort</td>
<td>Variability of effort deviations constrained by a prior distribution with (on the log scale) mean 0 and SD 0.22 (SD is 0.7 for Philippines, Indonesian and research longline fisheries with missing effort data).</td>
</tr>
<tr>
<td>Natural mortality</td>
<td>Age-dependent but constant over time and among regions. Smoothing penalties constrain the age-dependency.</td>
</tr>
<tr>
<td>Movement</td>
<td>Age-dependent but constant over time and among regions. Age-dependency for each coefficient (2 per region boundary) is linear.</td>
</tr>
</tbody>
</table>
Figure 1. Long-distance (>1,000 nmi) movements of tagged skipjack.
Figure 2. Distribution of skipjack catch 1972–1999 for the major fleets. The definition of the six regions used in the MULTIFAN-CL analysis is shown. Note that the size of circles reflects only spatial differences in catches within each fleet category.
Figure 3. Distribution of total skipjack catches 1972-1999 in relation to the six-region spatial stratification used in the MULTIFAN-CL analysis.

Figure 4. Skipjack tuna catch in the WCPO, 1970-2001.
Figure 5. Catch per unit effort by fishery. Units are relative to the average CPUE in each fishery.
Figure 6. Observed (circles) and predicted (lines) total catches by fishery and quarter. Catches are in tonnes for all fisheries except the longline (LL) fisheries, where the catches are in number of fish.
Figure 7. Observed (histograms) and predicted (line) length frequencies for each fishery aggregated over time.
Figure 8. Observed (circles) and predicted (lines) tag returns: (A) by calendar quarter, (B) by time at liberty, and (C) by calendar quarter for various fisheries (groups).
Figure 9. Estimated tag-reporting rates by fishery (histograms). The prior mean ±2 SD is also shown for each fishery.
Figure 10. (A) Estimated mean lengths-at-age, ± 2 SD of length-at-age. (B) Estimates of mean length-at-age (line) assuming age zero at length zero, and age-length observations of tagged skipjack recaptured after at least 3 months at liberty (circles). The age-length observations were obtained by estimating age at release using the inverse of the MULTIFAN-CL growth curve and adding the time at liberty.
Figure 11. Selectivity coefficients, by fishery. All JP PL fisheries were assumed to have common selectivity.
Figure 12. Estimated time-series catchability trends for each fishery.
Figure 13. Effort deviations by time period for each fishery.
Figure 14. Estimated natural mortality rate by age-class with 95% confidence intervals.
Figure 15. Relative distributions over time of cohorts recruited in each region.
Figure 16. The estimated origin of recruits (different patterns within bars) for skipjack sub-populations in each region (different bars). Sub-populations are computed at equilibrium and in the absence of fishing.
Figure 17. Time-series of estimated skipjack recruitment: (a) quarterly total recruitment (circles) and a moving 4-quarter average (heavy line), (b) 95% confidence intervals for total recruitment, and (c) quarterly recruitment and moving average for each region.
Figure 18. Estimated total skipjack relative biomass by region.

Figure 19. Estimated annual average fishing mortality rates for juvenile and adult age-classes.
Figure 20. Comparison of the estimated biomass trajectories (lower heavy lines) with biomass trajectories that would have occurred in the absence of fishing (upper thin lines) for (a) the WCPO (with the percentage difference in the trajectories also plotted in gray), and (b) each region.
Figure 21. Spawning biomass – recruitment estimates and the fitted Beverton and Holt stock-recruitment relationship (SRR) incorporating a prior on steepness of 0.9. The dashed lines are the 95% confidence intervals on the SRR.

Figure 22. Predicted equilibrium yield and 95% confidence intervals as a function of fishing mortality (relative to the average fishing mortality-at-age during 1997-2001).
Figure 23. Predicted equilibrium yield assuming constant equilibrium recruitment, as a function of fishing mortality (relative to the average fishing mortality-at-age during 1997-2001). The two curves represent recruitment at two average levels corresponding to early (1972–1984) and recent (1985–2001) estimated recruitment.
Figure 24. Ratios of (a) $F_t / F_{MSY}$ and (b) $B_{t, adult} / B_{MSY}^{adult}$ with 95% confidence intervals. The horizontal lines at 1.0 in each case indicate the overfishing (a) and overfished state (b) reference points.