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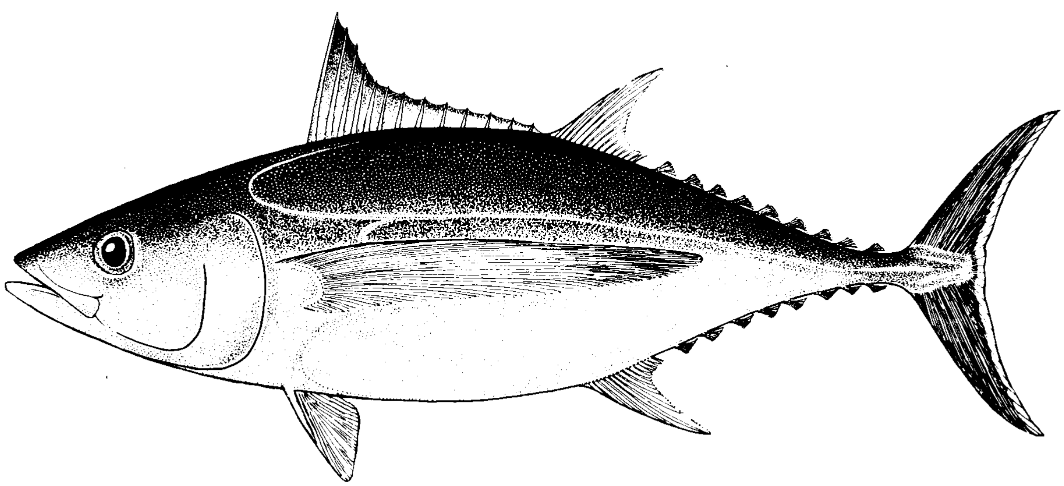
Stock assessment of albacore tuna in the south Pacific Ocean



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1 Background

1.1 Biology

Albacore tuna comprise a discrete stock in the South Pacific Ocean (Murray 1994). Adults (larger than about 80 cm FL) spawn in tropical and sub-tropical waters between about 10°S and 25°S during the austral summer (Ramon and Bailey 1996), with juveniles recruiting to surface fisheries in New Zealand coastal waters and in the vicinity of the sub-tropical convergence zone (STCZ – about 40°S) in the central Pacific about two years later, at a size of 45–50 cm fork length (FL). From this region, albacore appear to gradually disperse to the north (Figure 1), but may make seasonal migrations between tropical and sub-tropical waters.

Albacore are relatively slow growing, and have a maximum fork length (FL) of about 120 cm. They grow at a rate of approximately 10 cm per year from ages 2 to 4, with growth rate declining in a classic von Bertalanffy fashion thereafter (Labelle et al. 1993).

The natural mortality rate is believed to be in the region of 0.2–0.4 yr^{-1}, with significant numbers of fish reaching an age of 10 years or more. The longest period at liberty for a recaptured tagged albacore in the South Pacific is currently 11 years.

1.2 Fisheries

Distant-water longline fleets of Japan, Korea and Taiwan, and domestic longline fleets of several Pacific Island countries catch primarily adult albacore over a large proportion of their range (Figure 2). In recent years, the longline catch has expanded considerably with the development or expansion of small-scale longline fisheries in several Pacific Island countries, notably Samoa, American Samoa, Fiji, Tonga, Cook Islands, New Caledonia and French Polynesia. A troll fishery for juvenile albacore has occurred in New Zealand coastal waters since the 1960s and in the central Pacific in the region of the STCZ since the mid-1980s. Driftnet vessels from Japan and Taiwan targeted albacore in the central Tasman Sea and in the central Pacific near the STCZ during the 1980s and early 1990s. Surface fisheries are highly seasonal, occurring mainly during December to April, while longline fisheries operate throughout the year.

Total annual catches of South Pacific albacore have varied between 20 000 t and 52 000 t since the 1960s (Figure 3). Longline gear accounts for the majority of the catch, about 30 000 t per year on average. Final figures for 2001 are not yet available, but the longline and total catches are expected to be at record levels. Troll catches are relatively small, generally producing less than 10 000 t per year. The driftnet catch reached 22 000 t in 1989, but has since declined to zero following a United Nations moratorium on industrial-scale driftnetting.

2 Data compilation

The data used in the South Pacific albacore 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.

2.1 Spatial stratification

The geographic area considered in the assessment is the entire Pacific Ocean south of the equator and east of 140°E, an area defined by the Albacore Research Group of the SCTB for research and assessment purposes. Within this area, albacore show distinctive size segregation by latitude, with the smallest fish being found to the south. Therefore, a simple three-region spatial stratification was adopted for the assessment. The three regions consist of latitudinal bands of 0–10°S, 10°–30°S and 30°–50°S stretching across the Pacific (see Figure 2). These strata are denoted as North (N), Central (C) and South (S), respectively.

2.2 Temporal stratification

The time period covered by the assessment is 1962–2000. 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. However for the South Pacific albacore fishery, not all fleets (i.e. vessels of a particular nationality) of longliners target albacore, and some fleets have changed their targeting practices over time. Therefore, some additional stratification of longliners into national fleets was deemed necessary in order to sufficiently capture the variability in fishing operations with respect to albacore. The thirteen fisheries defined for the purpose of this assessment are given in Table 1.

2.4 Catch and effort data

Catch and effort data were compiled according to the fisheries defined above. All catches were expressed in numbers of fish, with the exception of the driftnet fishery for which catches in weight were used. For the longline fisheries, effort was expressed in hundreds of hooks, while for the troll and driftnet fisheries, boat days fishing was used. For each fishery, data were aggregated into the three-region stratification. Longline data were aggregated by quarter and troll and driftnet fisheries by month over the period 1962–2000. The data used in the compilation of catch and effort data were derived from a variety of sources (mainly logsheet data and 5-degree-square-month aggregated data provided by fishing nations) and raised to represent the best estimates of total catches as presented in the most recent version of the SPC Tuna Fishery Yearbook. Details of the methods used in compiling the data are as follows:

<u>Japanese longline</u> (fisheries 1, 4, 8). Catch and effort data have been provided by the National Research Institute of Far Seas Fisheries (NRIFSF) at 5 degree square, month resolution for the period 1962–2000. These data were originally derived from logbook samples and have been raised to represent the total catch. For the purpose of this assessment, Australia-Japan and NZ-Japan joint venture operations south of 30°S have been included in the Japanese longline fishery.

<u>Korean longline</u> (fisheries 2, 5, 9). Catch and effort data for Korean longliners have been provided in a variety of resolutions by the National Fisheries Research and Development Institute (NFRDI) of the Republic of Korea. For 1962–1974, only total annual catches in weight have been provided. For 1975–1987, catch in numbers and effort at 5 degree square, month resolution have been provided. For 1988–1993, catch in numbers and effort at 5 degree square, year resolution have been provided. Data for 1994–1997 are catch in number and effort at 5 degree square, month resolution. Finally, only total catch estimates (in weight) are available for 1998–2000. The estimates for 1962–1974, 1988–1993 and 1998–2000 have been converted to 5-degree-square-month format to be consistent with the remaining data. For 1962–1974, the temporal and spatial distribution of size compositions samples collected at the main unloading port (Pago Pago, American Samoa) for each year have been used to approximate the distribution of catch and effort to 5 degree square, month resolution. These samples have also been used to estimate catch in number from catch in weight. Effort is defined as "missing" for these years. For

1988–1993, the monthly catch and effort for each 5 degree square were estimated by applying the monthly average distributions of effort for the period 1980–1987 for each 5 degree square. Finally, for 1998–2000, logbook data for Korean longliners provided by SPC member countries and aggregated to 5 degree square, month resolution were raised to an estimate of the catch for the SPC statistical area. The proportion of the total catch occurring in the SPC statistical area was based on that observed for 1995–1997. For that proportion of the 1998–2000 catch occurring outside the SPC statistical area, the 1995–1997 average distribution of catch by 5 degree square and month was used to disaggregate the catch in this area. Catches in numbers were estimated from average weights derived from available size composition samples.

Taiwanese longline (fisheries 3, 6 and 10). Catch in number and effort data for the Taiwanese distant-water longline fleet at 5 degree square, month resolution have been provided by the National Taiwan University (1967–1993) and the Overseas Fisheries Development Council of the Republic of China (OFDC) through the Council of Agriculture (1994–2000). These data have been raised to represent landings (Lawson 1997). For 1964–1966, only annual catch weight estimates are available. The 5 degree square, month distributions of catch in these years have been estimated from the temporal and spatial distributions of size composition samples collected at the main unloading port (Pago Pago, American Samoa) for each year. These samples have also been used to estimate catch in number from catch in weight. Effort is defined as "missing" for these years.

Pacific Island longline (fishery 7). This fishery includes fleets based in American Samoa, Australia (east coast north of 30°S), American Samoa, Cook Islands, Fiji, French Polynesia, Kiribati, Marshall Islands, New Caledonia, Papua New Guinea, Samoa, Solomon Islands, Tonga and Vanuatu. Logbook data submitted by these countries to the OFP have been aggregated into 5 degree square, month format and raised to estimates of their total annual catches.

NZ domestic troll (fishery 11). Estimates of catch in weight and effort by 5 degree square and month for the period 1982–2000 have been provided by the NZ Ministry of Agriculture and Fisheries (MAF). Catch in numbers have been derived by applying average weights estimated from size composition samples. For the period 1967–1981, only estimates of total annual catch in weight are available. These catches have been disaggregated by month using the distribution of the later data.

STCZ troll (fishery 12). Catch in weight and effort for US vessels has been provided by the US National Marine Fisheries Service (NMFS) at 5 degree square, month resolution for the period 1986–2000. Likewise, data for NZ vessels has been provided by MAF at the same resolution. Catches in numbers have been determined from average weights estimated from size composition samples.

Driftnet (fishery 13). Catch in number and effort data (based on kilometers of net) by 5 degree square month have been provided by NRIFSF in respect of the Japanese driftnet fleet. Equivalent data for the Taiwanese fleet have been provided by the National Taiwan University. As there is some difference in effort units used by the Japanese and Taiwanese fleets, we have standardized Taiwanese driftnet effort to equivalent Japanese units by dividing the Taiwanese catches by the monthly Japanese CPUE. Note that the coverage of the entire South Pacific driftnet fishery represented by these data is unknown but is likely to be high.

A summary of the catch per unit effort (CPUE) is given in Figure 4.

2.5 Length-frequency data

Available length-frequency data for each of the defined fisheries were compiled into 90 1-cm size classes (30–120 cm). Each length-frequency observation consisted of the actual number of albacore measured. The data were collected from a variety of sampling programmes, which can be summarized as follows:

Japanese, Korean and Taiwanese longline: The majority of the historical data were collected by a NMFS port sampling programme in Pago Pago, American Samoa from 1962 onwards. Data collected from Japanese longliners not unloading in American Samoa have also been provided by the National Research Institute of Far Seas Fisheries. In recent years, data have also been collected by OFP port samplers from Taiwanese longliners unloading in Fiji.

Pacific Island longline: Length-frequency data for these fleets have been collected by port sampling programmes in most of the countries involved and by SPC or domestic observer programmes.

NZ domestic troll: Data have been collected from port sampling programmes conducted by the Ministry of Agriculture and Fisheries and, more recently, NIWA.

STCZ troll: Length-frequency data have been collected by port sampling programmes in Levuka (Fiji), Pago Pago (American Samoa) and Papeete (French Polynesia), and, during 1990–91 and 1991–92, by scientific observers.

Driftnet: Data have been provided by the National Research Institute of Far Seas Fisheries in respect of Japanese driftnet vessels. Data from Japanese vessels were also collected by observers and by port sampling in Noumea, New Caledonia. It is assumed that these data are representative of Taiwanese vessels also.

2.6 Tagging data

A limited amount of tagging data was available for incorporation into the MULTIFAN-CL analysis. The data used consisted of tag releases and returns from the OFP's albacore tagging programme conducted during the summers of 1990–91 and 1991–92. Tags were released using standard tuna tagging equipment and techniques by trained scientists and scientific observers. In 1990–91, a limited amount of tagging was conducted from a chartered pole-and-line fishing vessel in New Zealand coastal waters. In both years, the majority of tag releases were made by scientific observers on board New Zealand and U.S. troll vessels fishing in New Zealand waters and in the central South Pacific STCZ region.

For incorporation into the MULTIFAN-CL analysis, tag releases are stratified by release region (all albacore releases occurred in the southern region), time period of release (quarter) and the same size classes used to stratify the length-frequency data. A total of 9,691 releases were classified into 5 tag release groups (released in Q4 1990, Q1 1991, Q4 1991, Q1 1992 and Q2 1992) in this way. The returns from each size class of each tag release group (163 tag returns in total) were then classified by recapture fishery and recapture time period (quarter or month).

3 Structural assumptions of the model

As with any model, various structural assumptions have been made in the South Pacific albacore 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 (2001). The main structural assumptions used in the albacore model are discussed below and summarized 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 effective sample size and the observed length-frequency proportion. Effective sample size is assumed to be 0.1 times the actual sample size for all fisheries, with a maximum effective sample size of 100. Reduction of the effective sample size recognises that length-frequency samples are not truly random and would have higher variance as a result.

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 (2001) (Appendix C).

3.2 Tag reporting

We attempted to estimate tag-reporting rates with relatively uninformative Bayesian priors as there is little independent information available. There appeared to be also little information in the data to sustain estimation of reporting rates. A sensitivity analysis was therefore carried out constraining the maximum reporting rate to various levels. For the base-case results presented here, we constrained the maximum reporting rate (for the various fisheries) to be 0.2. Note that this parameter is actually a composite of several possible tag-loss processes. In addition to non-reporting of recaptured tags, a significant source of tag loss for albacore could also be immediate mortality due to tagging.

3.3 Tag mixing

We assume that tagged albacore gradually mix with the untagged population at the region level and that this mixing process is complete after one year at liberty.

3.4 Recruitment

"Recruitment" in terms of the MULTIFAN-CL model is the appearance of age-class 1 fish in the population. Given the observation in the fisheries statistics that catches of juvenile albacore tend to occur mainly in the cooler temperate waters of the South Pacific, and biological observations of the distribution of reproductive activity (Ramon and Bailey 1996), it was assumed that South Pacific albacore recruitment occurs only in the southern region of the model domain.

From visual inspection of the length-frequency data, the apparent seasonality of reproduction (Ramon and Bailey 1996) and previous growth analyses (Labelle et al. 1993), it was further assumed that recruitment is an annual event that occurs in June. An alternative hypothesis of four recruitments per year was also tested. This analysis gave similar overall results, but did not significantly improve the overall fit to the data. We therefore opted to retain the annual recruitment model because of its greater simplicity. The time-series variation in 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.

Recruitment was assumed to have a weak relationship with the spawning 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 2001, 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). The prior was specified by mode = 0.9 and SD = 0.04 (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 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, 12 annual age classes have been assumed; however a wide range of alternative assumptions (12 through 15 age classes) have been shown to have little impact on the model results.

3.6 Selectivity

Selectivity is fishery-specific and was assumed to be time-invariant. Selectivity coefficients have a range of 0−1, and for the longline fisheries (which catch mainly adult albacore) were assumed to increase with age and to remain at the maximum once attained. The 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).

3.7 Catchability

Catchability was assumed to be constant over time for the TWLL fisheries in the central and southern regions. This assumption was based on the fact that these fisheries have consistently targeted albacore in these regions over a long period using similar operational methods. Catchability for all other fisheries was allowed to vary slowly over time (akin to a random walk) using a structural time-series approach. Random walk steps were taken biennially, and the deviations constrained by a prior distribution of mean zero and a variance equivalent to a CV of 0.10 on the log scale. Seasonal variation in catchability was also modelled in order to explain the strong seasonal variability in CPUE for most of the fisheries.

3.8 Effort variability

Effort deviations, constrained by prior distributions of zero mean and variance equivalent to a CV of approximately 0.2 on the log scale, were used to model the random variation in the effort – fishing mortality relationship.

3.9 Movement

Movement was assumed to occur instantaneously at the beginning of each year. Each of the four movement coefficients was allowed to be age-dependent in a simple linear fashion and was assumed to be constant over time.

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 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.

4 Results of the base-case analysis

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 5) as expected, reflecting the assumption that observation errors in the total catch estimates are relatively small.

The fit to the length data is displayed in Figure 6a for length samples aggregated over time for each fishery. Figure 6a 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. The modal structure evident in the surface fisheries is well represented by the model predictions, while the shape and location of the length distributions of all fisheries is reasonably 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. An example of the fit to the time-series data (for the NZ troll fishery) is shown in Figure 6b. The modes in the data for this fishery and the STCZ troll and driftnet fisheries are well estimated by the model and interpreted as annual age classes. Overall, the growth dynamics evident in the data appear to be well captured by the model.

The fits of the model to the tagging data compiled by calendar time and by time at liberty are shown in Figure 7. The fits appear to be satisfactory, given the relatively low number of tag returns.

4.2 Tag-reporting rates

As noted earlier, tag-reporting rate is very ill-determined for South Pacific albacore. The approach taken was to set an upper limit on the reporting rate, which in the base-case analysis was 0.2. The tag-reporting estimates for the distant-water longline fisheries were highest for the Taiwanese fleet, intermediate for Japanese fleet and lowest for the Korean fleet (Figure 8). Reporting rates for the surface fisheries are also relatively low.

4.3 Age and growth

The estimates of mean length-at-age and the variability in length-at-age are shown in Figure 9. Also plotted on this figure for comparison are estimates of mean length for presumed annual ring counts obtained from albacore vertebrae (Labelle et al. 1993). There is good agreement between the MULTIFAN-CL estimates and the annual ring counts assuming that the first age class in the MULTIFAN-CL analysis is 2 years of age.

4.4 Selectivity

The selectivity coefficients (Figure 10) reflect the age-specific exploitation characteristics of each fishery. Albacore appear to be fully recruited to the longline fisheries by about age 10. In the southern region, longline selectivity is quite different to the estimates for the northern and central region. Apparently, small juvenile albacore are more vulnerable to longline in this region than in the more northerly regions.

4.5 Catchability

We assumed independent catchability amongst all the fisheries. There are several time-series changes in the estimated catchability (Figure 11). Catchability for the Japanese and Korean longline fisheries are estimated to have declined rapidly during the 1960s, particularly in the northern and central regions. This is presumably related to the switch from albacore to yellowfin and bigeye targeting by these fleets. Catchability for the Taiwanese longline fishery in the central and southern regions were assumed to be constant. Seasonal catchability is a feature in most of the fisheries.

The overall consistency of the model with the observed effort data and the catchability assumptions can be examined in plots of effort deviations against time for each fishery (Figure 11). If the model is coherent with the effort data, we would expect an even scatter of effort deviations about zero. Some outliers would also be expected, which prompted the use of robust estimation techniques. On the other hand, if there was an obvious trend in the effort deviations with time, this may indicate that a trend in catchability had occurred and that this had not been sufficiently captured by the model. No unusual variability in the residuals is apparent in Figure 11, suggesting that the model has probably extracted all the information present in the data regarding catchability variation.

4.6 Natural mortality

The natural mortality rate is estimated to be about 0.3 yr^{-1} for juvenile albacore, with an increase to about 0.5 yr^{-1} beginning at around the size of 70 cm (Figure 12). As noted in previous reports, the sex ratio of albacore changes rapidly with increasing size to favour males. This raises the possibility that M may be greater for older fish because of high female mortality associated with the physiological demands of spawning.

4.7 Movement

A representation of the dispersal patterns resulting from the estimated movement parameters is shown in Figure 13, which shows the changes in the relative distributions over time of cohorts originating in each region. Movement occurs more rapidly from the southern to the central region than in the reverse direction. The amount of movement from the central to the northern region is very small. Southerly movement from the northern region is also rapid. Note that all tags were released in the southern region, so movement rates from this region will likely be better determined than those from the other regions.

4.8 Recruitment

The recruitment estimates show considerable interannual and lower frequency variation (Figure 14). The pattern is similar to the previous analysis (Fournier et al. 1998), with recruitment being generally higher prior to 1980. The lower recruitments during the 1980s were then followed by some increase during the early 1990s. Since the mid-1990s, recruitment has been below average. The possible effect of oceanographic variability on several time scales on albacore recruitment is the subject of ongoing study.

The precision of the total recruitment estimates is indicated by the approximate 95% confidence intervals in Figure 14. For the whole period considered by the model, the confidence intervals are larger prior to 1980 and during the last couple of years of the time-series. The degradation of recruitment estimates at the end of the time series is a common feature of age-structured models.

4.9 Biomass trends

Time-series trends in total and adult biomass are shown in Figure 15. Biomass declined to historic lows in the late 1980s and recovered to some extent during the 1990s. Similar patterns are evident in all regions.

4.10 Fishing mortality and the impact of fishing

Estimates of average annual fishing mortality rates for juvenile (age classes 1−5) and adult (age classes 6−12) albacore are shown in Figure 16. There was a spike in juvenile fishing mortality in the late 1980s associated with the driftnet fishery. Longline (adult) fishing mortality rates have increased strongly since the mid-1980s. The decline in the final year is a result of incomplete data. In fact, catches of adult albacore are known to have increased significantly in 2001 as a result of developments in Pacific Island longline fleets.

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 the south Pacific are shown in Figure 17. The estimated impact is relatively slight (about 10% in 2000).

4.11 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 <u>overfishing</u>; and the biomass at MSY (B_{MSY}) is used as an indicator of an <u>overfished state</u>. 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 yellowfin tuna assessment, the average F_{age} over 1994–1999 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 $B_t^{total} / B_{MSY}^{total}$, $B_t^{adult} / B_{MSY}^{adult}$, F_t / F_{MSY} and their 95% confidence intervals and comparing them with 1.0. Values of F_t / F_{MSY} significantly greater than 1.0 would indicate overfishing, while values of $B_t^{total} / B_{MSY}^{total}$ and/or $B_t^{adult} / B_{MSY}^{adult}$ 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 South Pacific albacore tuna is shown in Figure 18. 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-at-age given by the 1994–1999 average is shown in Figure 19. This analysis indicates that, at the 1994–1999 average F-at-age (i.e. a fishing mortality multiplier of 1.0), the equilibrium yield is approximately 38,000 t per year, which is similar to the observed catch over the base period. The maximum equilibrium yield (equivalent to MSY) of about 117,000 t is only achieved at a very high F-multiplier, around 16x.

The ratios of F_t / F_{MSY} and $B_t^{adult} / B_{MSY}^{adult}$ are shown in Figure 20. F_t / F_{MSY} has been well beneath the overfishing reference point throughout the time series. Also, while adult biomass has fallen in the second half of the time series, $B_t^{adult} / B_{MSY}^{adult}$ has remained above 1.0, indicating that the population has yet to reach an overfished state under the definition used here.

5 Sensitivity analysis

A sensitivity analysis was conducted to examine the effect of different constraints on the tag-reporting rate. As the maximum reporting rate is allowed to increase, absolute population size also increases, as indicated by the recruitment and biomass time series in Figure 21a, b. Fishery impact decreases with increasing maximum reporting rate. As expected, the equilibrium yield estimates (Figure 21d) are very sensitive to reporting rate because it controls absolute population size. The reference points

(Figure 21e, f) are increasingly optimistic (with respect to stock status) as the maximum reporting rate constraint is increased.

The overall fit of the model improved as the maximum reporting rate constraint was raised, although the degree of improvement did not suggest that the model could determine the reporting rate or absolute stock size with much accuracy. When the tagging data are completely removed from the analysis, abundance is even higher and fishing mortality smaller than the models with tagging data included. It seems that there is very little information in the catch, effort and size data on absolute abundance, and the small amount of tagging data available is not able to make much of an impact in the absence of informative assumptions about the tag-reporting rate.

6 Conclusions

The major stock assessment conclusions of the South Pacific albacore analysis are:

1. Recruitment was higher on average prior to 1980 and during the early 1990s. Recent recruitment levels have been below average, but these estimates are relatively imprecise.

2. Biomass levels have largely reflected the recruitment variation, peaking in the late 1970's. Current biomass is estimated to be approximately two-thirds of the maximum estimated level and about 85% of the estimated equilibrium unexploited biomass.

3. Fishing mortality is higher for adult albacore than for juveniles, reflecting the predominantly longline exploitation. Fishing mortality rates are lower than natural mortality rates over a plausible range of tag-reporting rates.

4. The impact of the fisheries on total biomass is estimated to have increased over time, but is likely to be low, a reduction of <20% from unexploited conditions.

5. The estimation of equilibrium yields as a function of fishing mortality and *F*- and *B*-based reference points is hampered by the very low resolution of absolute abundance estimates by the model. This is likely to result from the combination of low exploitation rates, a small amount of tagging data, and no independent information on tag-reporting rates. Nevertheless, over a plausible range of assumed tag-reporting rates, the model results indicated that current catches are less than the MSY, aggregate fishing mortality is less than F_{MSY} and the adult biomass is greater than B_{MSY}.

6. Research required to improve the quality of the South Pacific albacore assessment includes the following:

   - Improved estimates of total catch and fishing effort by Pacific Island longline fleets;
   - Information on vertical habitat utilization by albacore and gear configuration and fishing depth information for longline vessels targeting albacore, to enable estimation of effective longline fishing effort;
   - Accurate estimation of fishery impacts and sustainable yield ultimately requires information allowing more accurate estimation of absolute abundance. For widely distributed mobile species such as albacore, large-scale conventional tagging probably remains the only viable option.

7 Acknowledgements

We are grateful to all Standing Committee on Tuna and Billfish participants for provision of catch, effort and size composition data used in this analysis.

8 References

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Table 1. Definition of fisheries for the MULTIFAN-CL analysis of South Pacific albacore.

Fishery #		Nationality	Gear	Region
1	JPLL N	Japan	Longline	N
2	KRLL N	Korea	Longline	N
3	TWLL N	Taiwan	Longline	N
4	JPLL C	Japan	Longline	C
5	KRLL C	Korea	Longline	C
6	TWLL C	Taiwan	Longline	C
7	PILL C	Pacific Island countries	Longline	C
8	JPLL S	Japan, Australia, NZ	Longline	S
9	KRLL S	Korea	Longline	S
10	TWLL S	Taiwan	Longline	S
11	NZ TR	NZ	Domestic troll	S
12	STCZ TR	NZ, US, French Polynesia	STCZ troll	S
13	DN	Japan, Korea, Taiwan	Driftnet	S

Table 2. Main structural assumptions used in the albacore tuna analysis.

Category	Assumption
Observation model for total catch data	Observation errors small, equivalent to a residual SD on the log scale of 0.07.
Observation model for length-frequency data	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.
Observation model for tagging data	Tag numbers in a stratum have negative binomial probability distribution, with fishery-specific variance parameter
Tag reporting	Longline reporting rates within each fleet are constrained to be equal. Relatively uninformative prior for all fisheries. Base-case analysis has maximum reporting rate constrained to be <=0.2. This constraint is the subject of sensitivity analysis. All reporting rates constant over time.
Tag mixing	Tags assumed to be randomly mixed at the model region level from the quarter following the quarter of release.
Recruitment	Occurs as discrete events in June of each year in the southern region only. Recruitment is weakly related to spawning biomass in with a 2 year lag via a Beverton-Holt SRR (beta prior for steepness with mode at 0.9 and SD of 0.04).
Initial population	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 5 years of the analysis.
Age and growth	12 annual age-classes, with the last representing a plus group. Age-class 1 allowed an independent mean length; other 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=6.9587e-06, b=3.2351 estimated from available length-weight data).
Selectivity	Constant over time. Various smoothing penalties apply. Coefficients for the last 2 age-classes are constrained to be equal. Longline selectivities are non-decreasing with increasing age.
Catchability	Seasonal variation for all 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.
Fishing effort	Variability of effort deviations constrained by a prior distribution with (on the log scale) mean 0 and SD 0.22 for all fisheries.
Natural mortality	Age-dependent but constant over time and among regions. Smoothing penalties constrain the age-dependency.
Movement	Age-dependent but constant over time and among regions. Age-dependency for each coefficient (2 per region boundary) is linear.

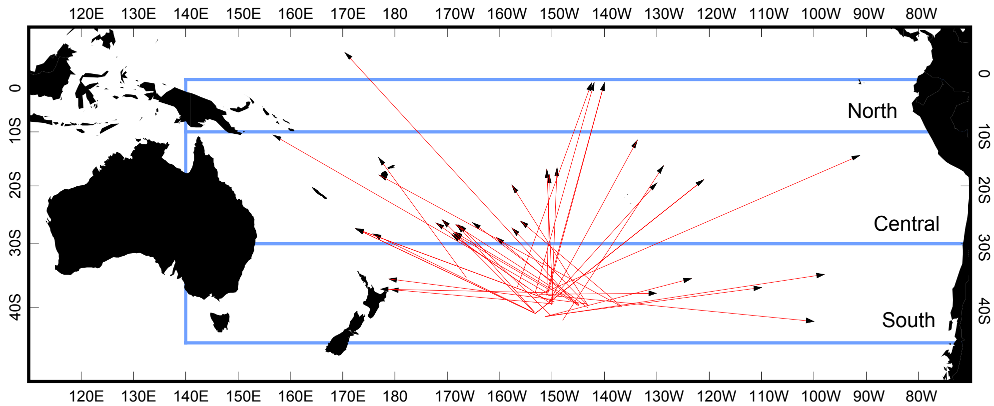

Figure 1. Movements of tagged South Pacific albacore. The spatial stratification used in the MULTIFAN-CL model is shown.

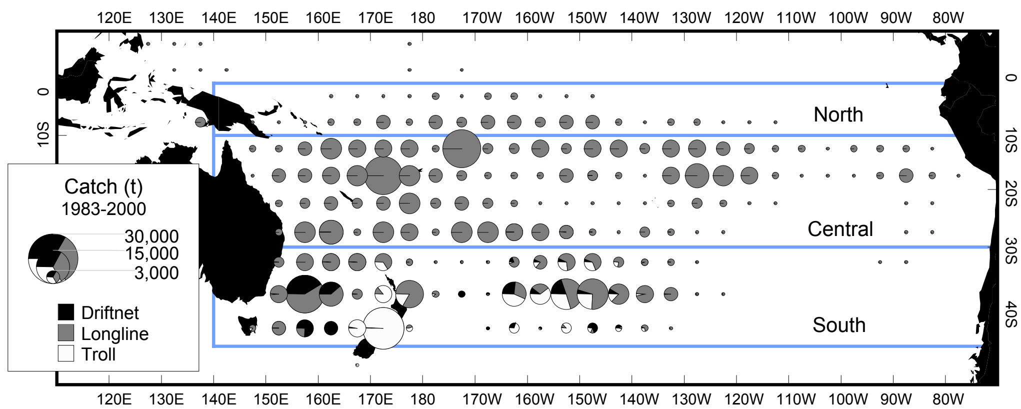

Figure 2. Albacore catch distribution (1983−2000) by fleet. The spatial stratification used in the MULTIFAN-CL model is shown.

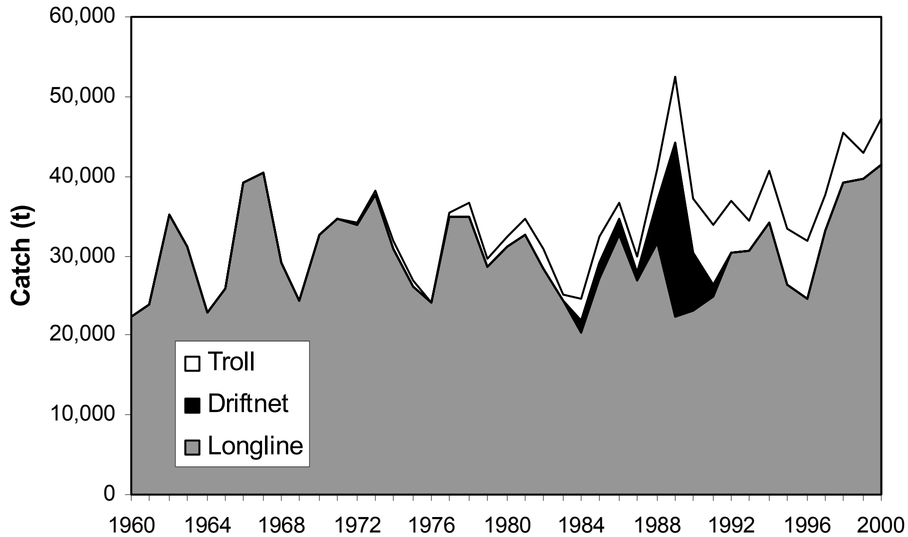

Figure 3. South Pacific albacore catch by gear type.

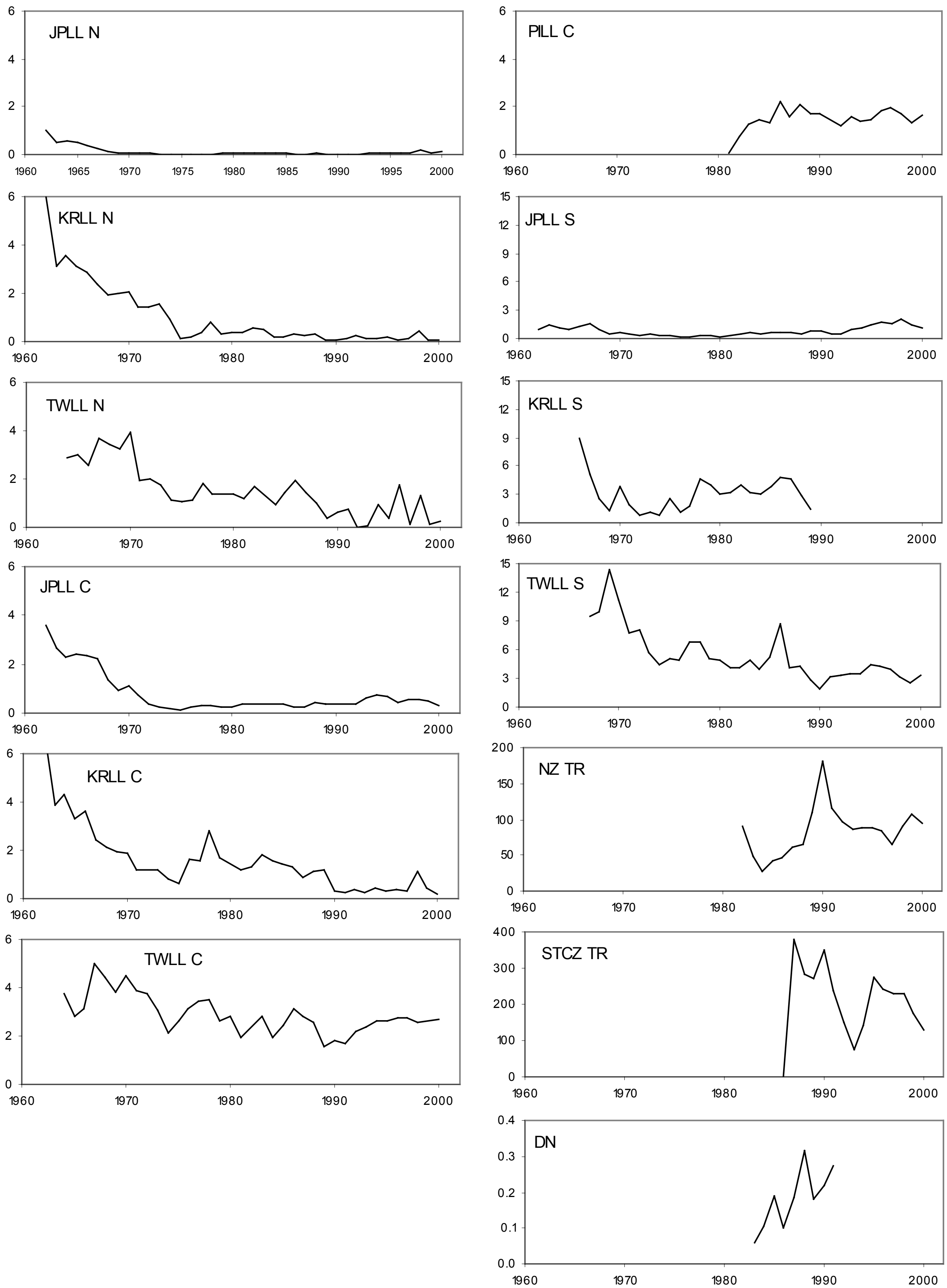

Figure 4. Catch per unit effort by fishery. Units are catch number per 100 hooks for the longline fisheries, catch number per day for troll fisheries and tonnes per day for the driftnet fishery.

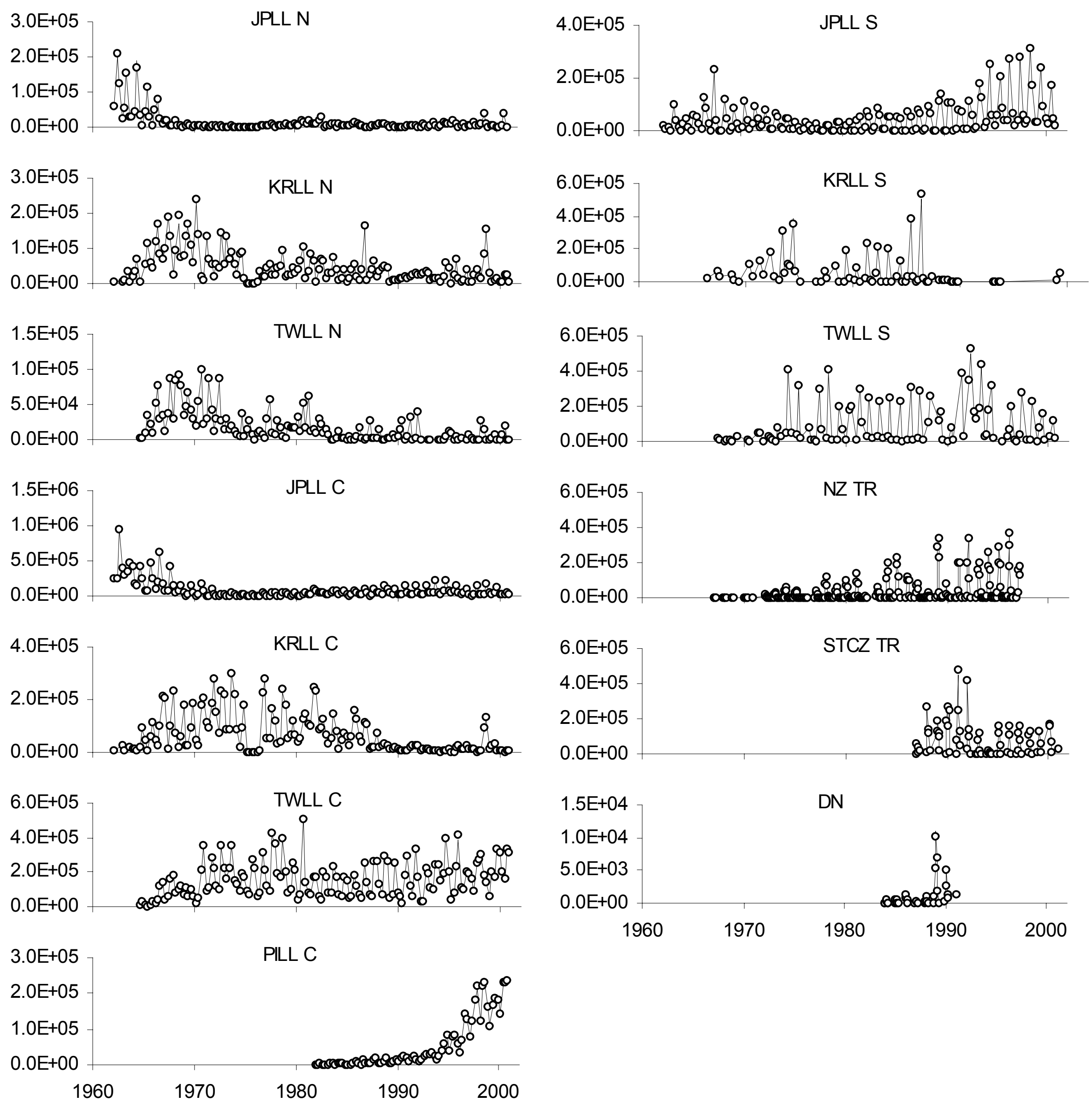

Figure 5. Observed (circles) and predicted (lines) total catches by fishery and quarter. Catches are in number for all fisheries except the driftnet (DN) fishery, where the catches are in tonnes.

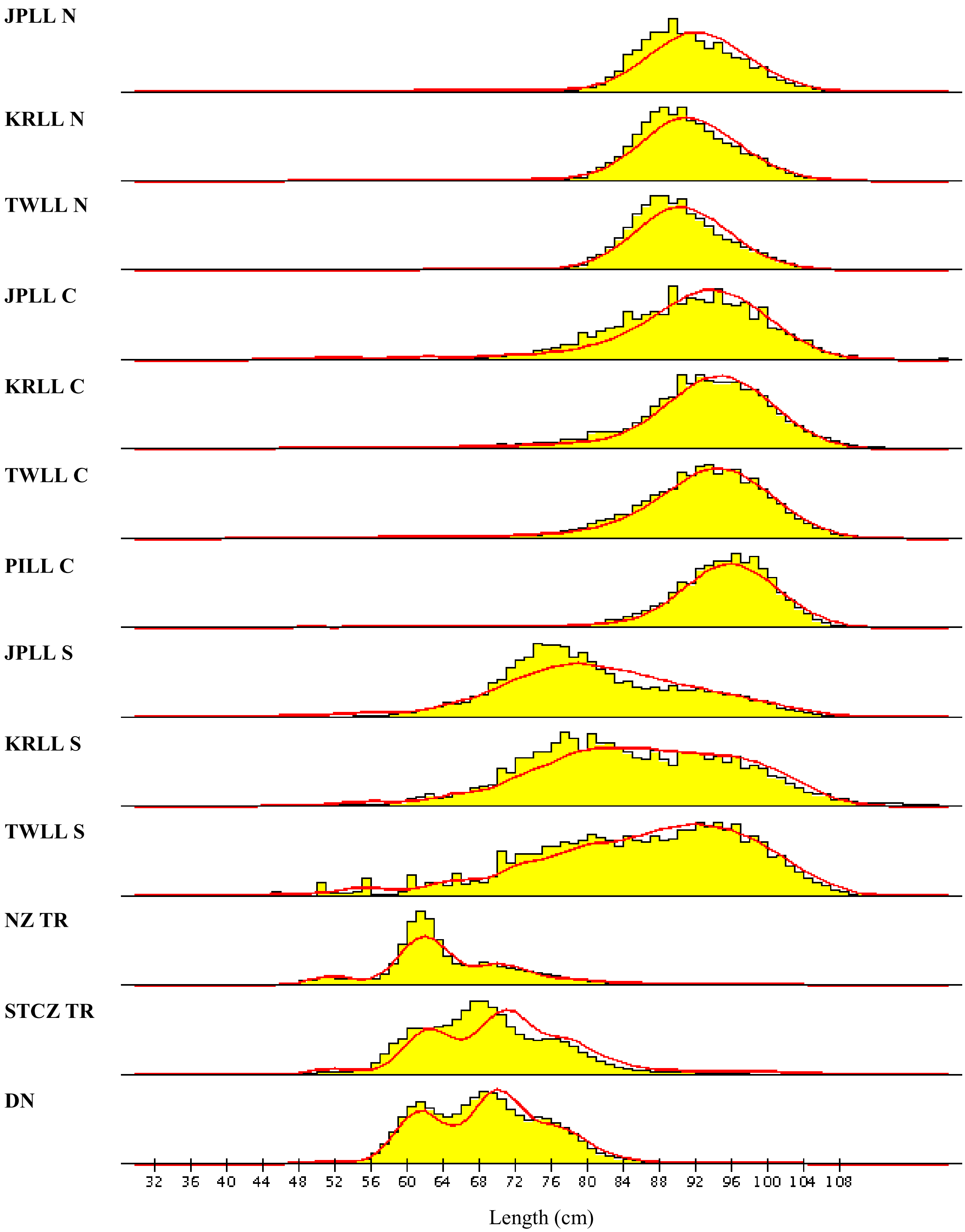

Figure 6a. Observed (histograms) and predicted (line) length frequencies for each fishery aggregated over time.

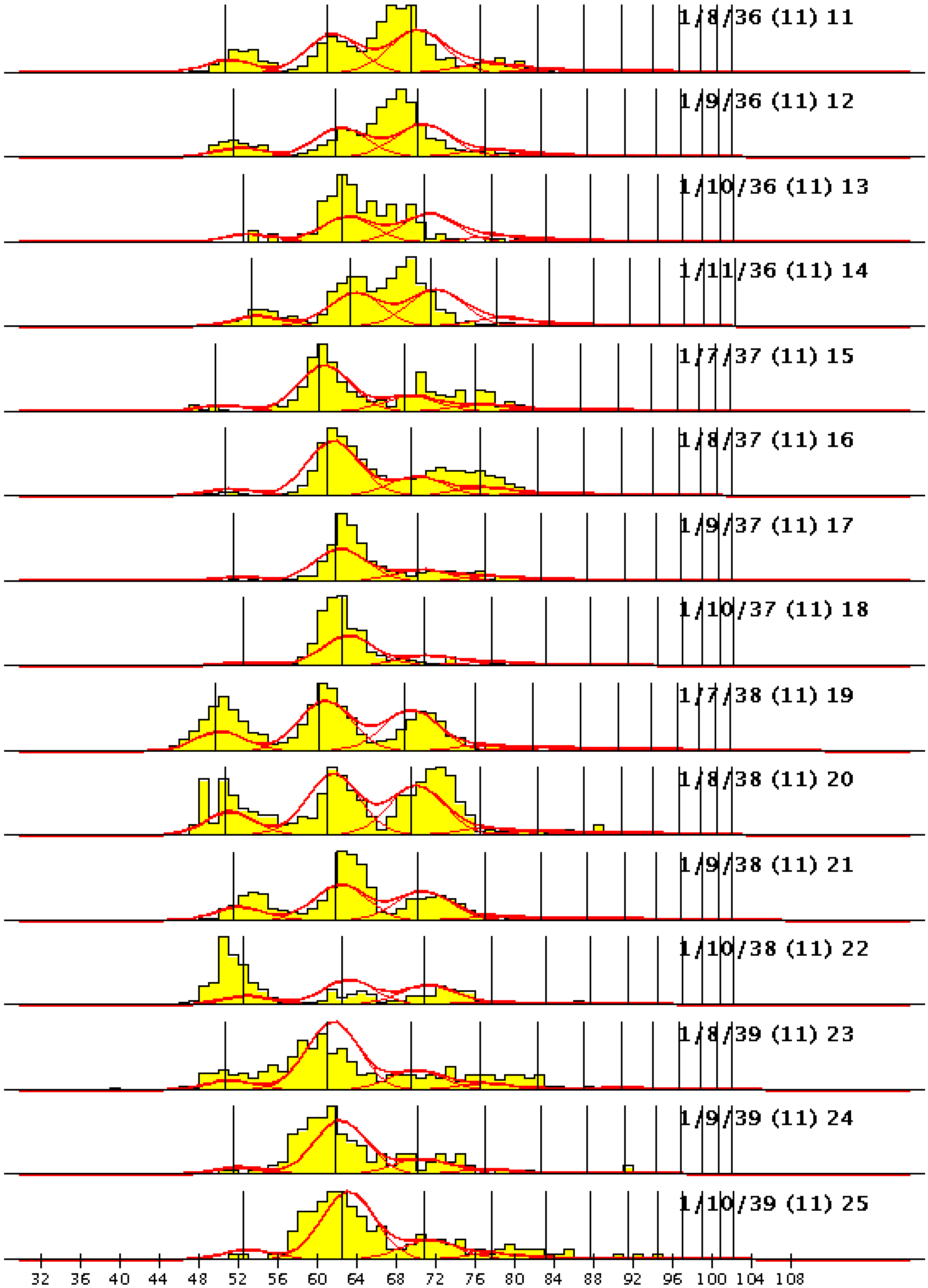

Figure 6b. Observed (histograms) and predicted (line) length frequencies for the New Zealand domestic troll fishery. The vertical bars indicate the estimated mean lengths-at-age.

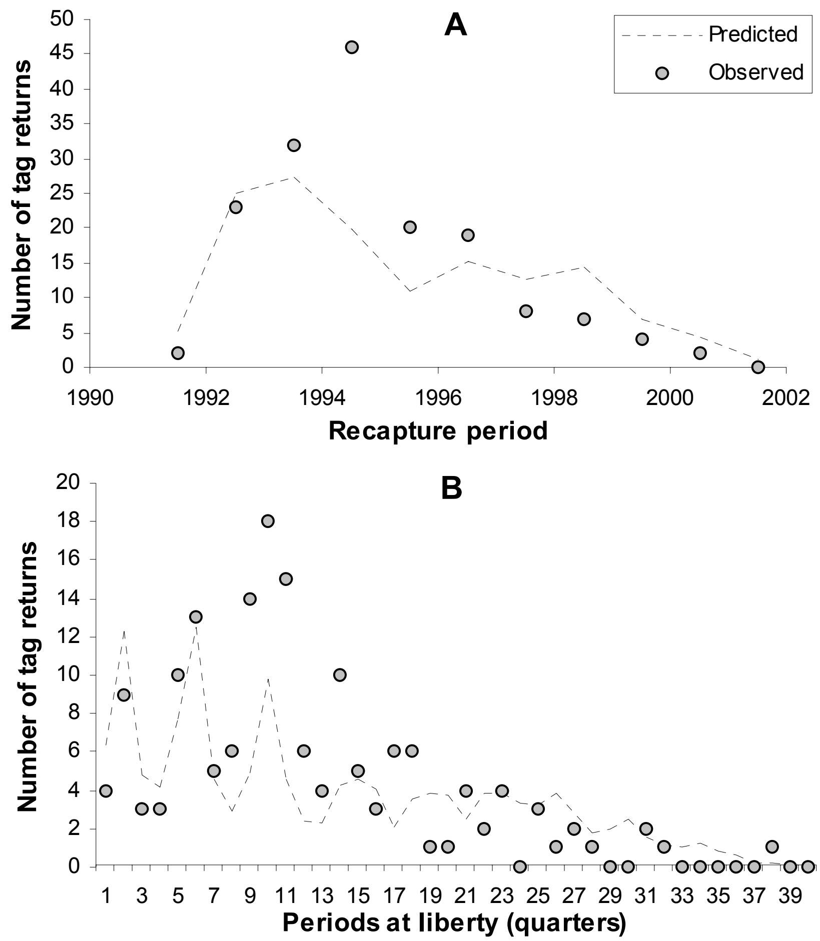

Figure 7. Observed (circles) and predicted (lines) tag returns (A) totals by recapture period, (B) totals by time at liberty.

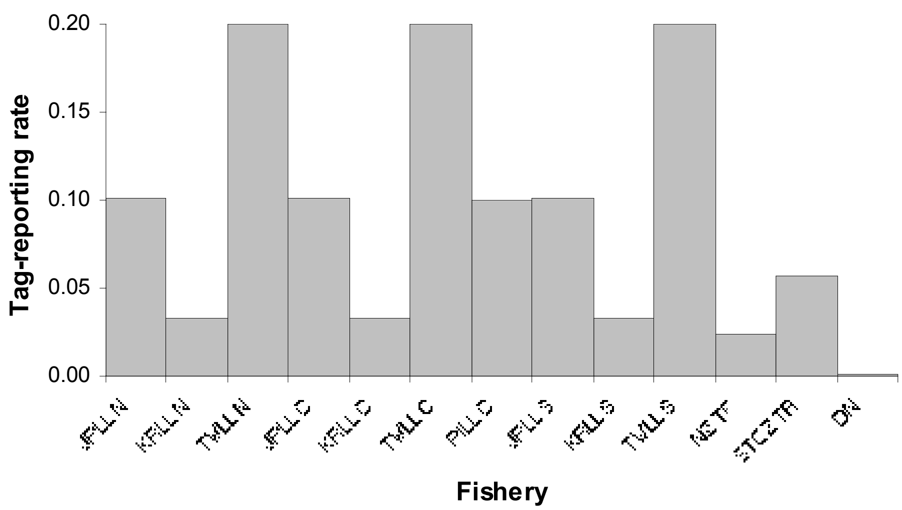

Figure 8. Estimated tag-reporting rates by fishery.

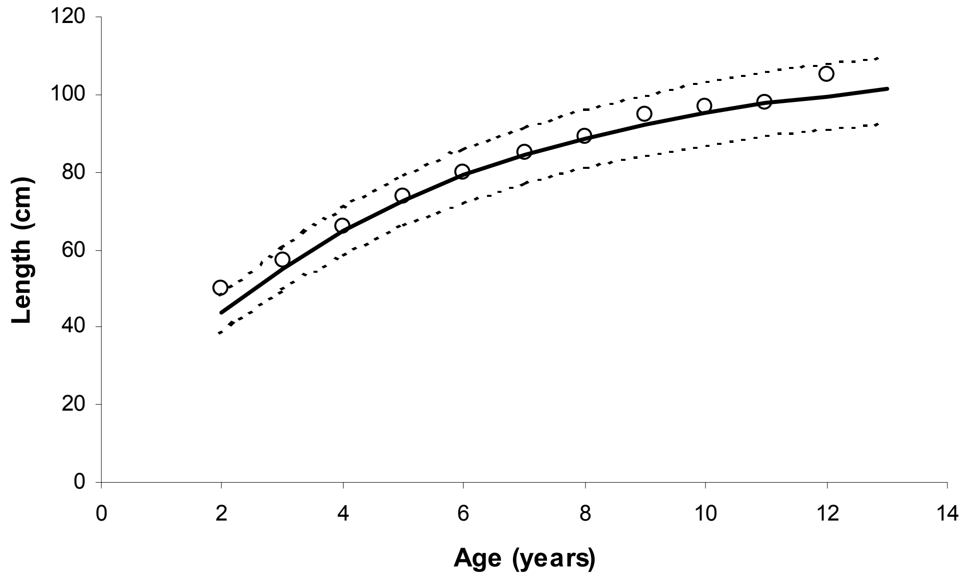

Figure 9. Estimated mean lengths-at-age (heavy line) and the variability of length-at-age (dotted lines represent ± 2 SD) assuming that the first age class is two years of age. The circles are mean lengths corresponding to annuli on South pacific albacore vertebrae (from Labelle et al. 1993).

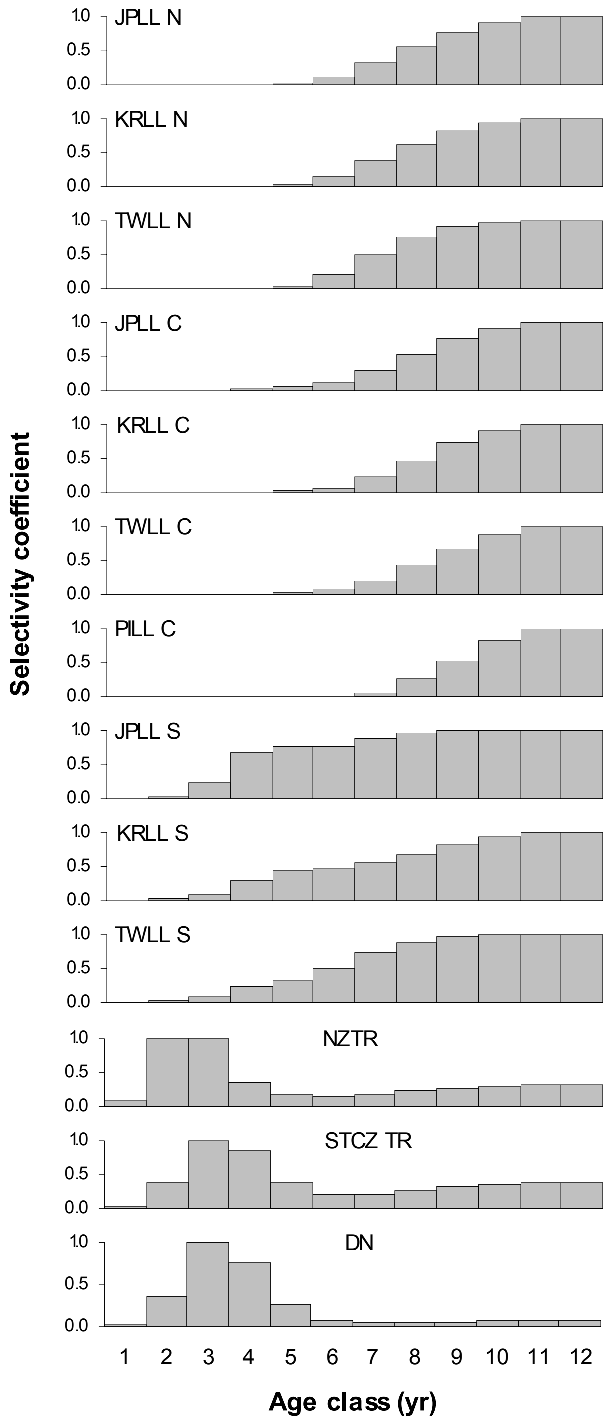

Figure 10. Selectivity coefficients, by fishery.

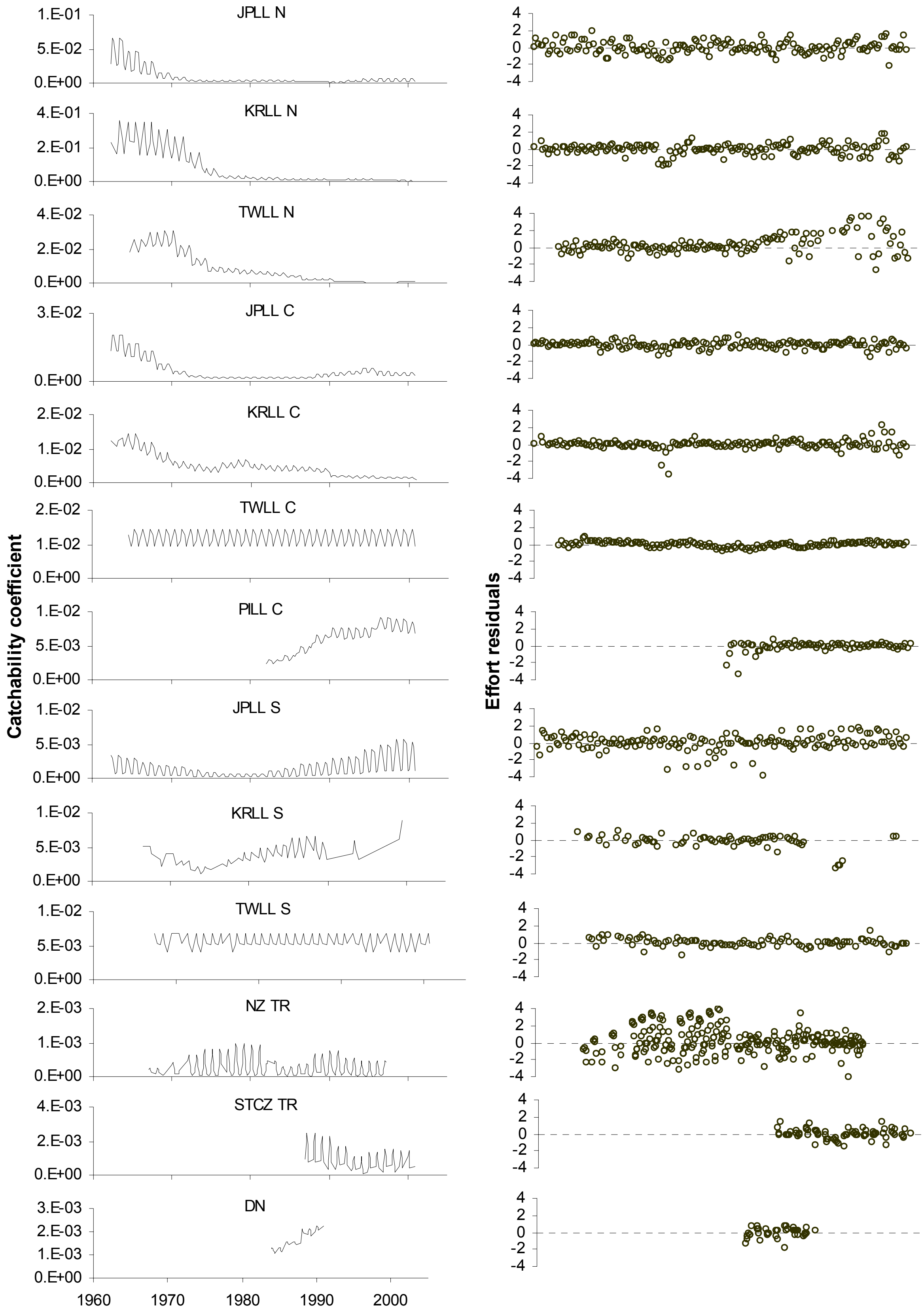

Figure 11. Catchability trends (left) and effort deviations (right), by fishery.

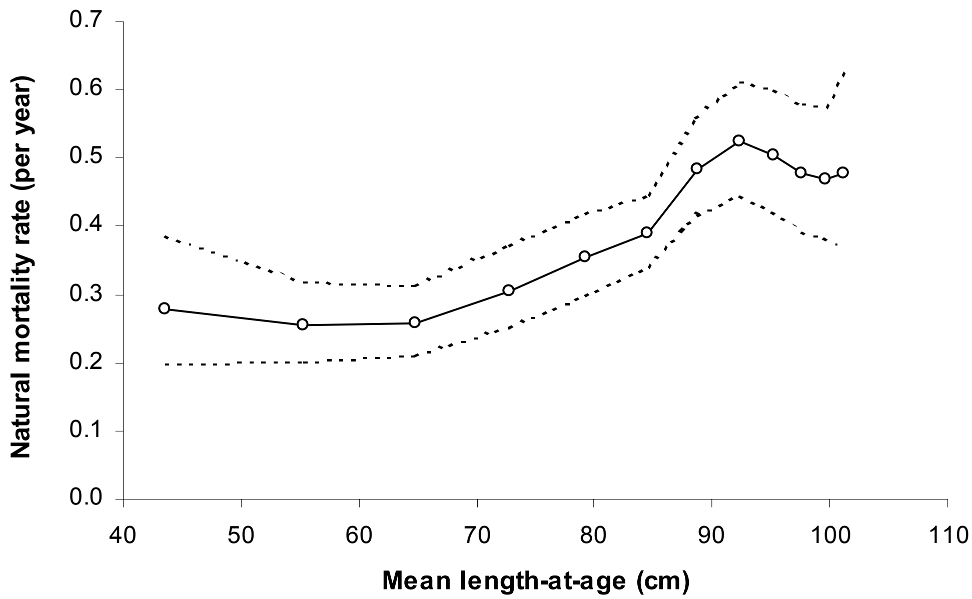

Figure 12. Estimated natural mortality rate by age-class plotted against mean length-at-age with 95% confidence intervals.

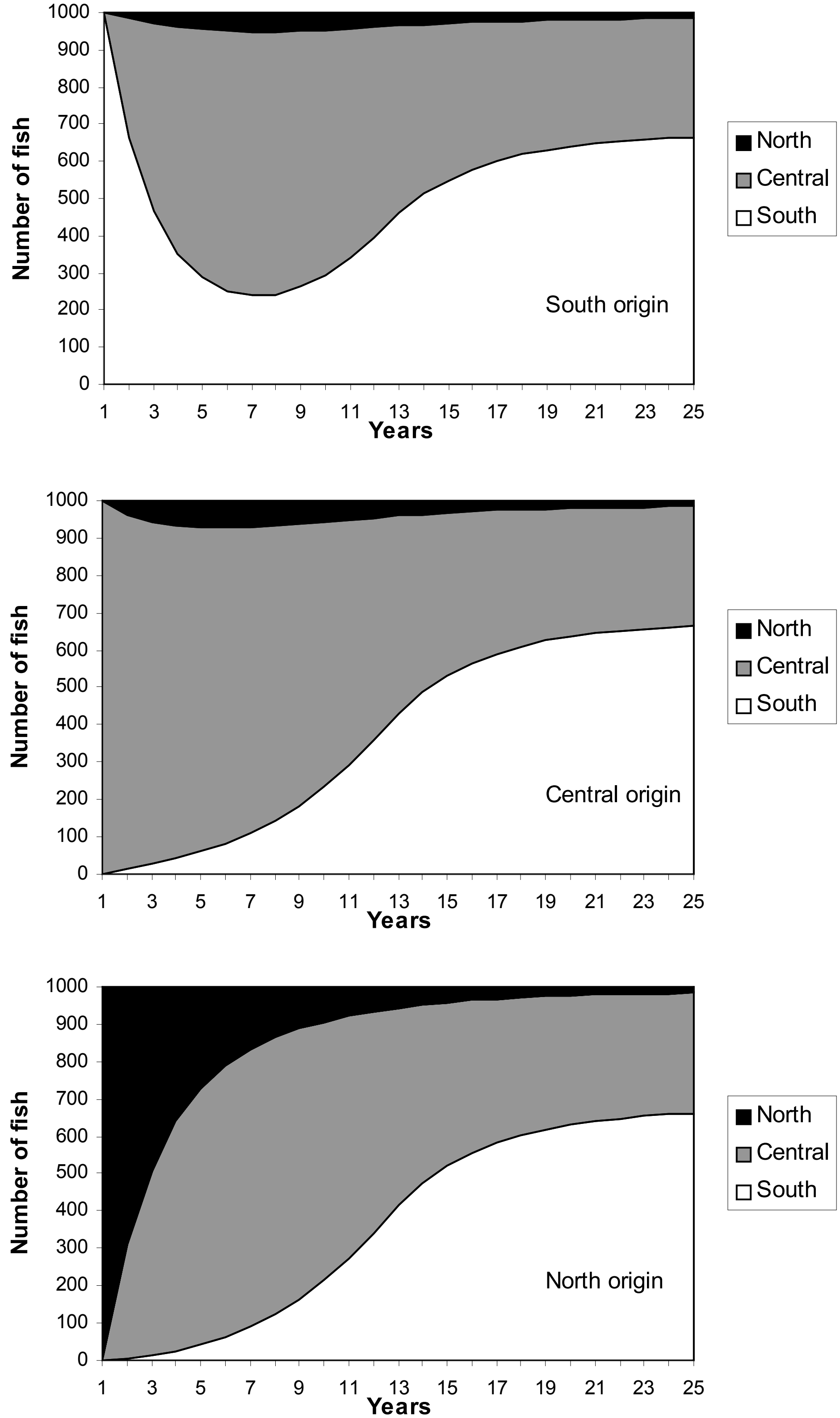

Figure 13. Relative distributions over time of cohorts recruited in each region.

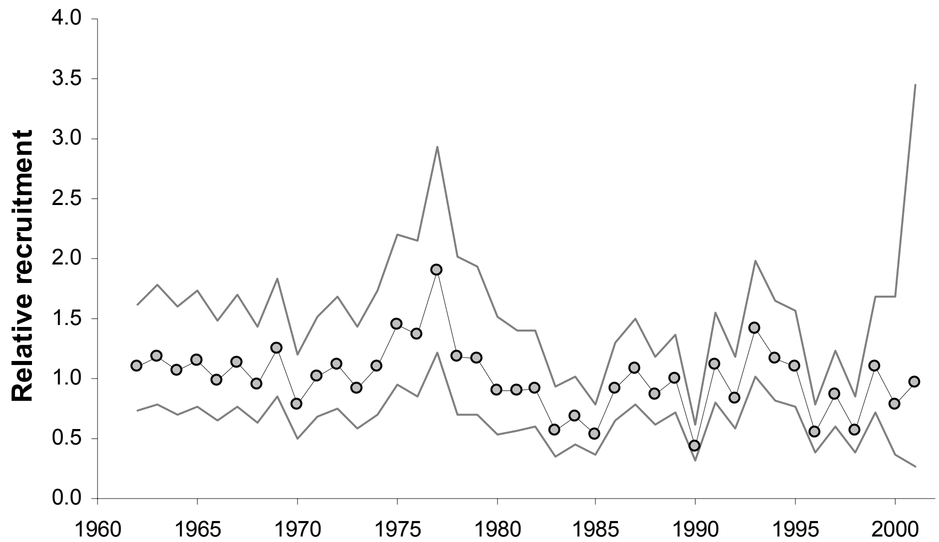

Figure 14. Estimated annual recruitment, with 95% confidence intervals. Estimates and confidence intervals are scaled to the average of the point estimates.

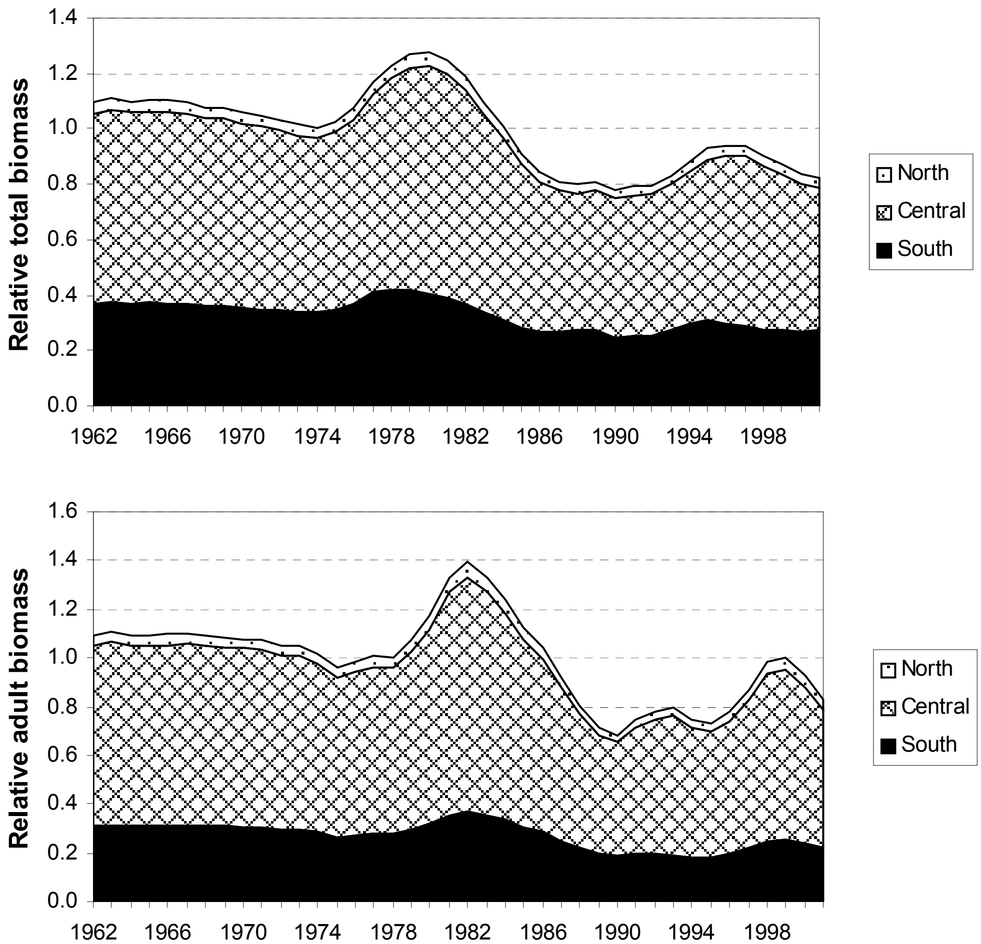

Figure 15. Estimates of relative total and adult biomass, by region.

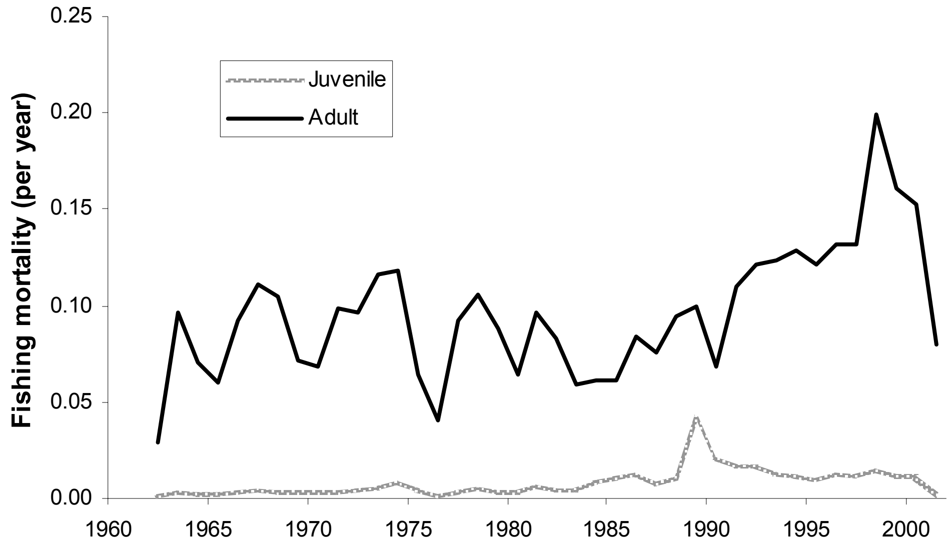

Figure 16. Estimated annual fishing mortality rates for juvenile (age-classes 1-5) and adult (age-classes 6-12) albacore in the South Pacific.

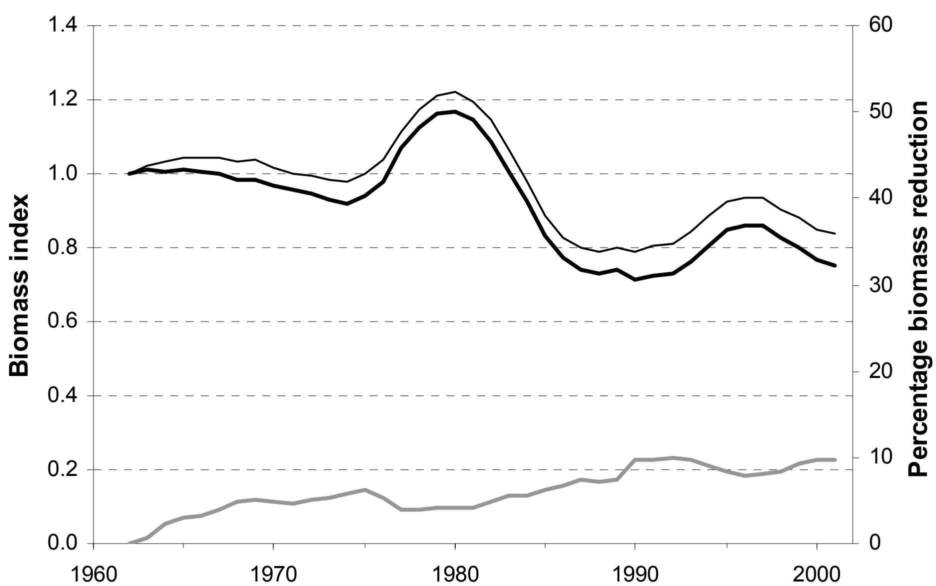

Figure 17. Comparison of the estimated biomass trajectory (lower heavy lines) with the biomass trajectory that would have occurred in the absence of fishing (upper thin lines). The lower grey line plots the percentage difference between the two trajectories.

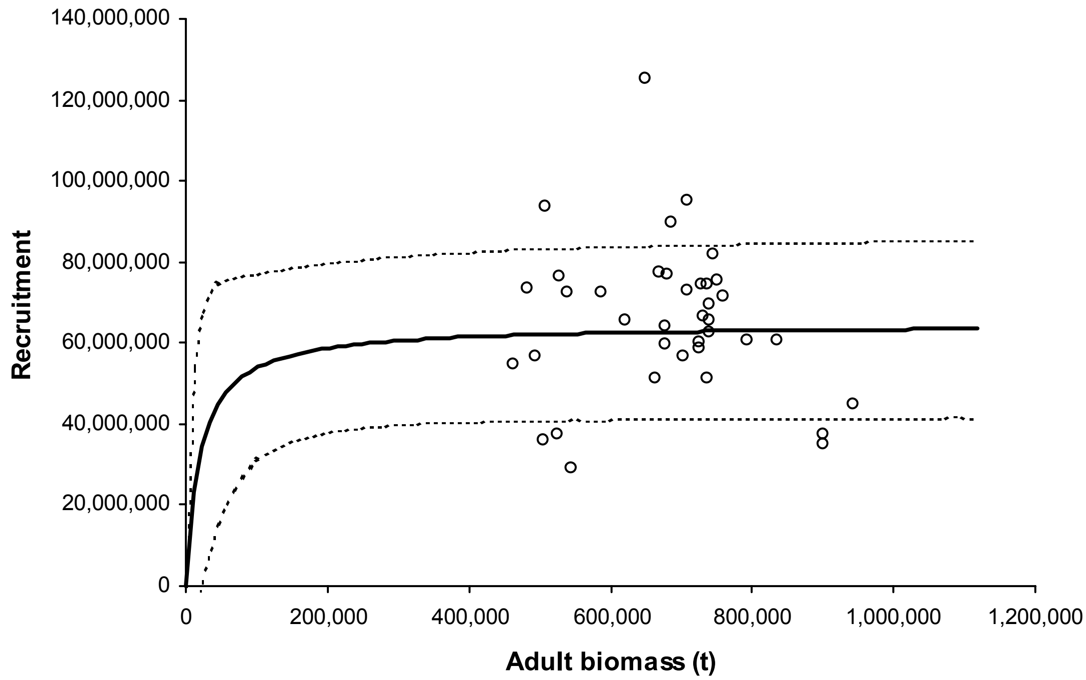

Figure 18. Spawning biomass – recruitment estimates and the fitted Beverton and Holt stock-recruitment relationship (SRR) incorporating a prior on steepness of 0.9. The dashed lines are the 95% confidence intervals on the SRR.

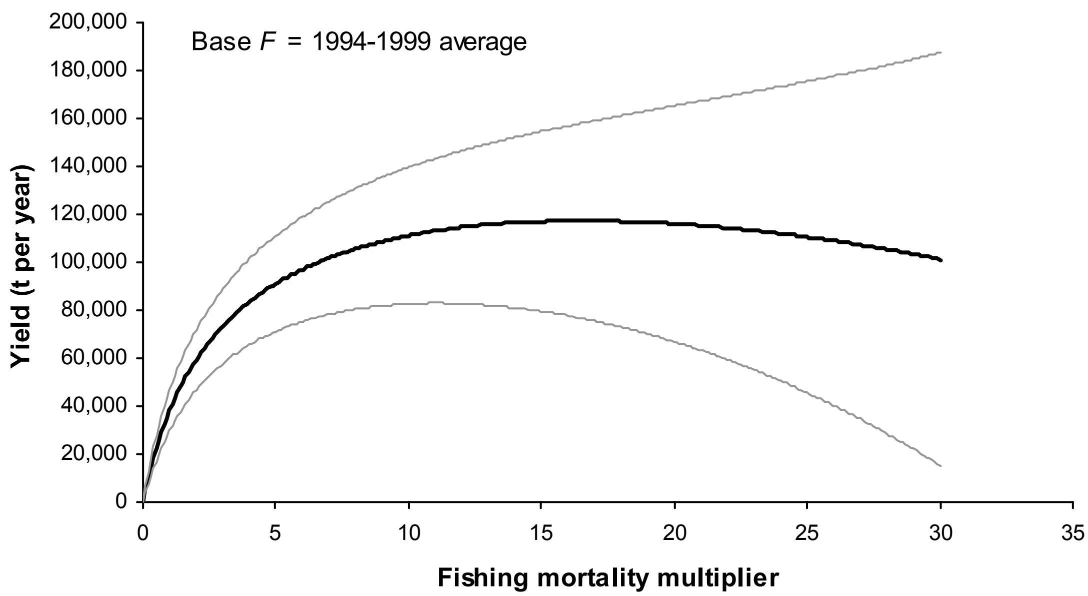

Figure 19. Predicted equilibrium yield and 95% confidence intervals as a function of fishing mortality (relative to the average fishing mortality-at-age during 1994-1999).

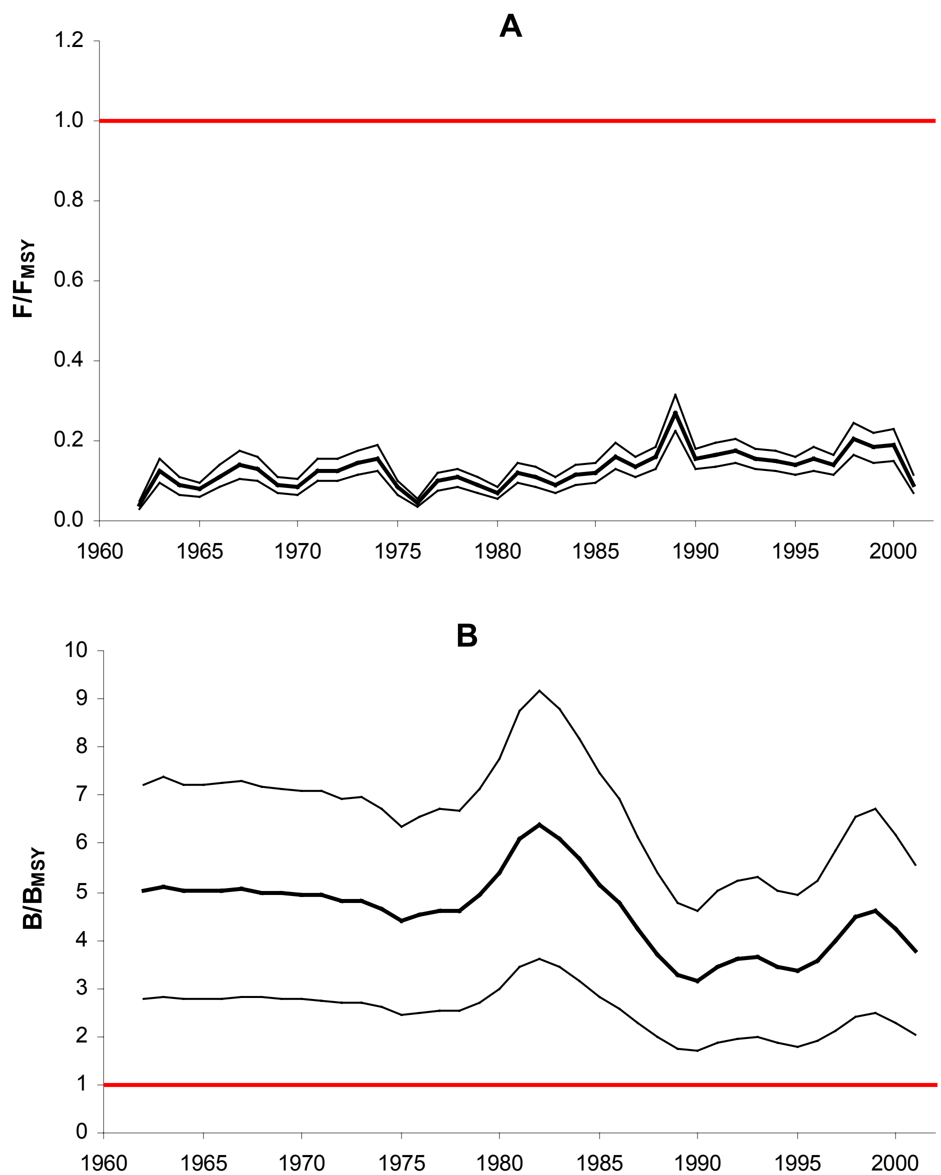

Figure 20. Ratios of (a) F_t / F_{MSY} and (b) $B_t^{adult} / B_{MSY}^{adult}$ with 95% confidence intervals. The horizontal lines at 1.0 in each case indicate the overfishing (a) and overfished state (b) reference points.

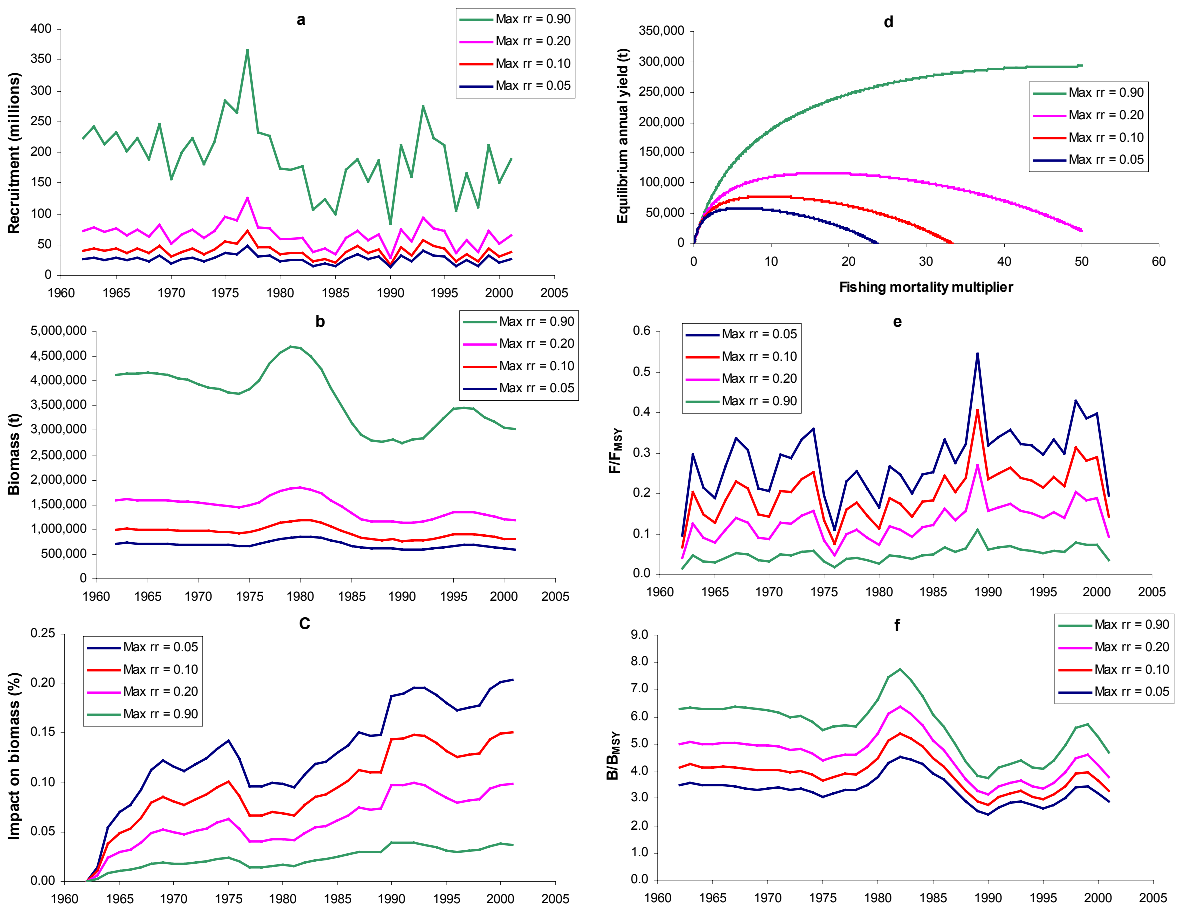

Figure 21. Sensitivity analysis of the effects of different constraints on the maximum tag-reporting rate on (a) recruitment; (b) biomass; (c) impact; (d) equilibrium yield; (e) F_t/F_{MSY} and (f) $B_t^{adult}/B_{MSY}^{adult}$.