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ALB–1

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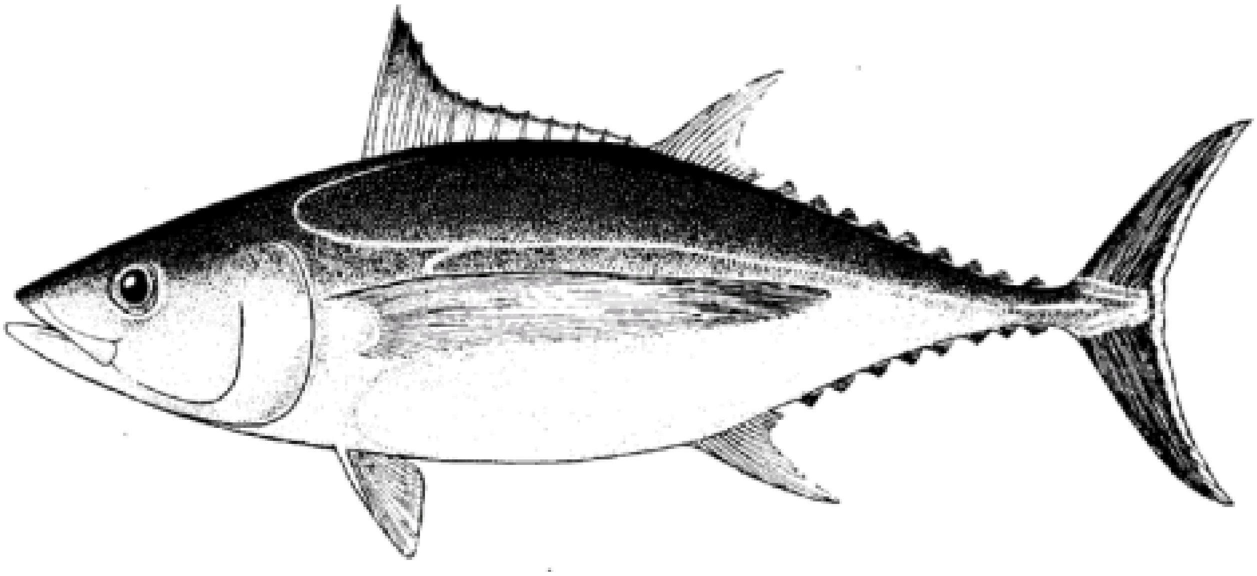
Stock assessment of albacore tuna in the south Pacific Ocean



Keith Bigelow[1], John Hampton[1] and David Fournier[2]

[1] Oceanic Fisheries Programme
Secretariat of the Pacific Community
Noumea, New Caledonia

[2] Otter Research Ltd.
PO Box 2040
Sidney, BC, Canada V81 3S3

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) 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.

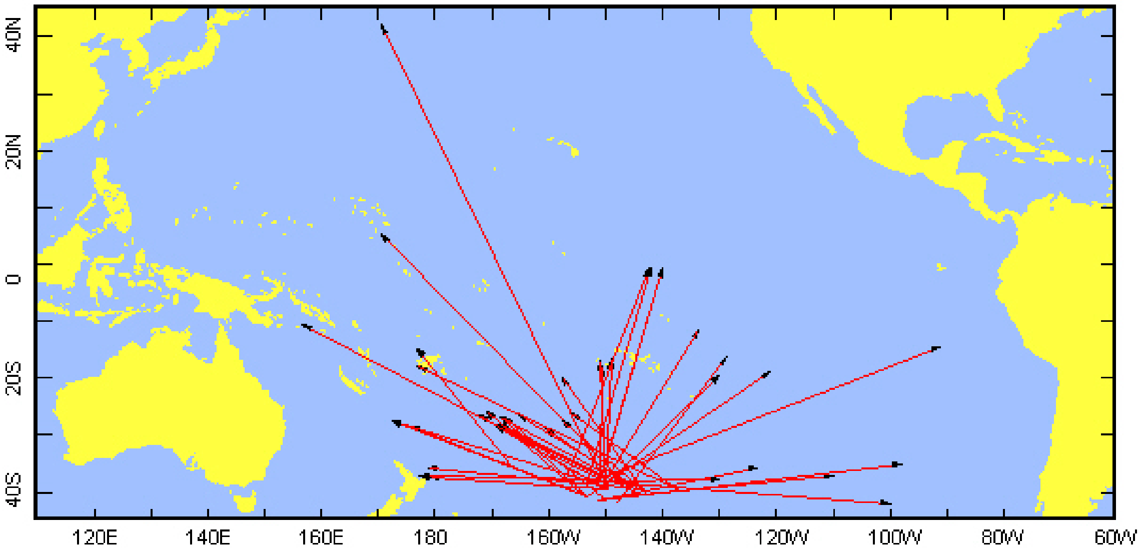


Figure 1. Movements of tagged South Pacific albacore.

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 2a–d). In recent years, a significant longline-type operation has developed in Samoa. The vessels are mostly small, outboard-powered catamaran *alias* and lines are set and hauled by hand. The range of this fishery is restricted to waters close to Samoa (Figure 2d). 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 (Figure 2f). 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 (Figure 2g). Surface fisheries are highly seasonal, occurring mainly during December to April, while longline fisheries operate throughout the year.

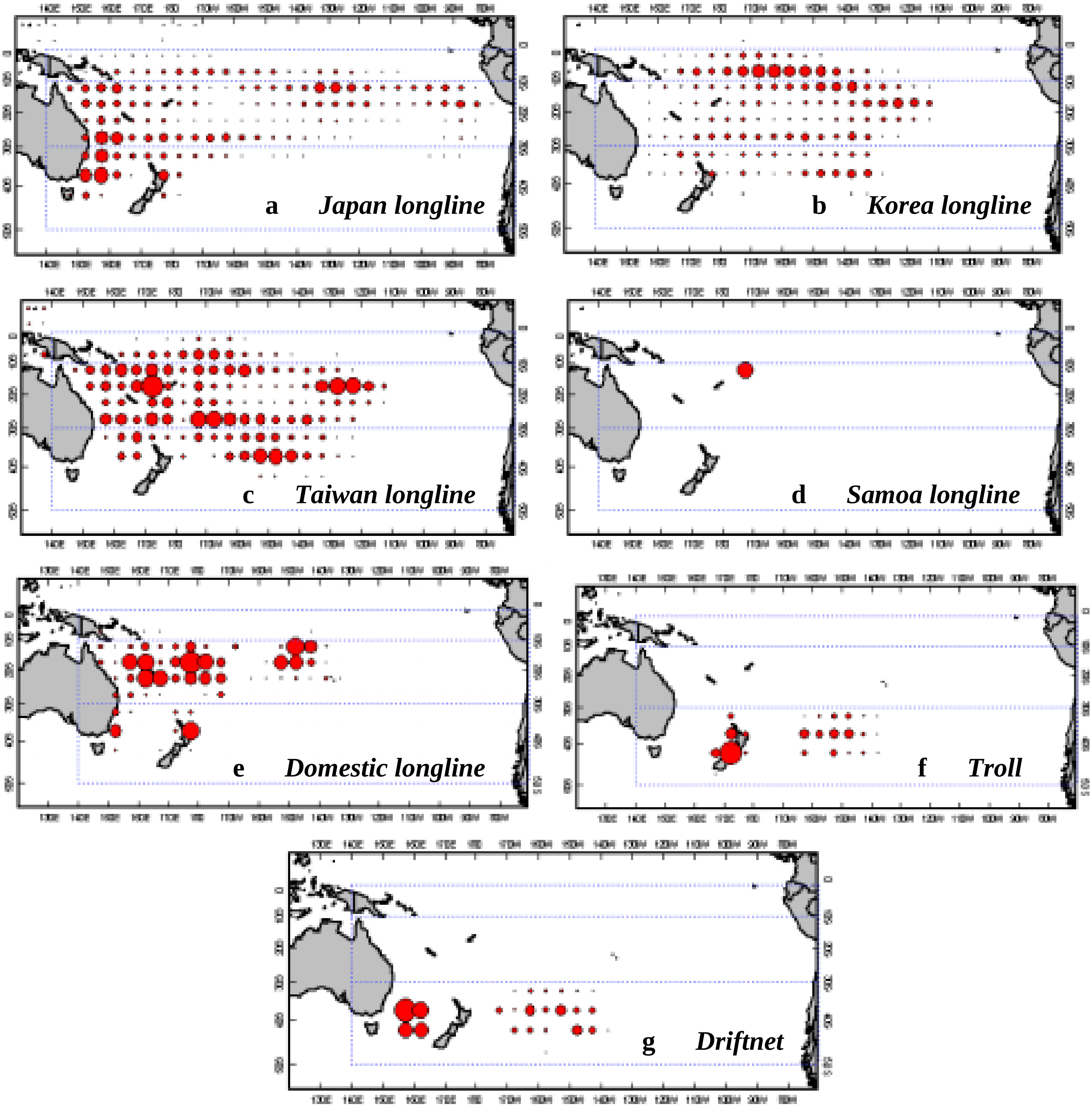


Figure 2. Albacore catch distributions (1962–2000) for various fleets fishing in the South Pacific. The dotted lines denote the spatial stratification used in the MULTIFAN-CL analysis.

Total annual catches of South Pacific albacore have varied between 20 000 t and 52 000 t since the 1960s. Longline gear accounts for the majority of the catch, about 30 000 t per year on average. Troll catches are relatively small, generally producing less than 10 000 t per year. The driftnet catch reached 27 000 t in 1989, but has since declined to zero following a United Nations moratorium on industrial-scale driftnetting. The time series of annual catches by gear is shown in Figure 3.

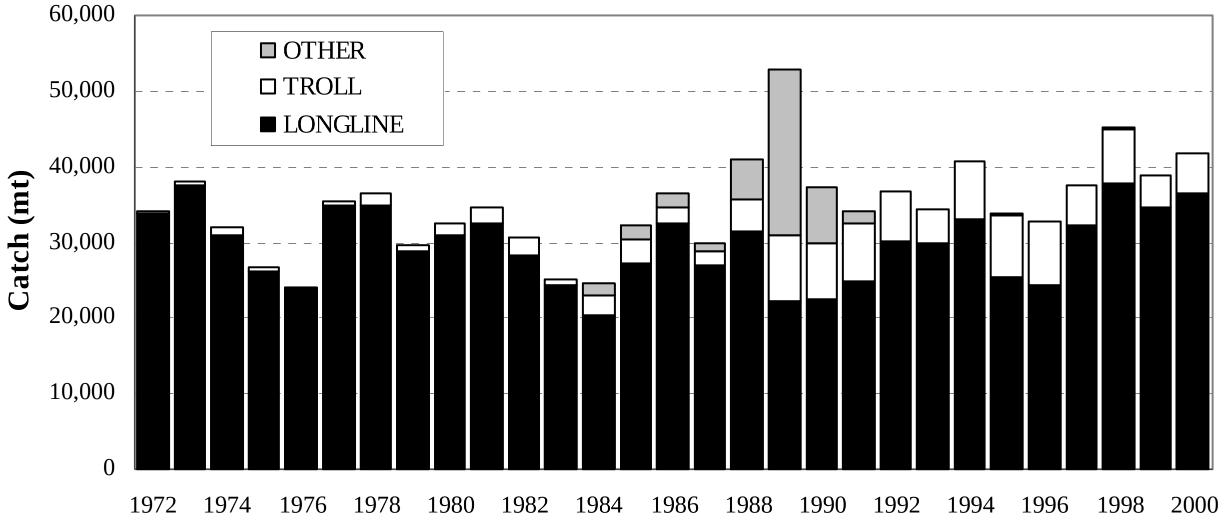


Figure 3. Total catch of South Pacific albacore, by gear type.

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 any of the maps in 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). However, it is seldom practicable or even necessary to stratify the data into a large number of fisheries so as to isolate all variability in these parameters. More fisheries means more parameter complexity, so a parsimonious approach is required. For most pelagic fisheries assessments, fisheries defined according to gear type, fishing method and region will usually suffice. 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 fourteen fisheries defined for the purpose of this assessment are as follows:

	Fishery #	Nationality	Gear	Region
1	JPLL–3	Japan	Longline	N
2	KRLL–3	Korea	Longline	N
3	TWLL–3	Taiwan	Longline	N
4	JPLL–2	Japan	Longline	C
5	KRLL–2	Korea	Longline	C
6	TWLL–2	Taiwan	Longline	C
7	DOM–LL	Miscellaneous Pac. Is.	Longline	C
8	JPLL–1	Japan, Australia, NZ	Longline	S
9	KRLL–1	Korea	Longline	S
10	TWLL–1	Taiwan	Longline	S
11	DOM–TROLL	NZ	Domestic troll	S
12	INT–TROLL	NZ, US, Fr. Poly.	STCZ troll	S
13	DRIFTNET	Japan, Korea, Taiwan	Driftnet	S
14	SAMOA–LL	Samoa	Alia longline	C

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. 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 required three-region and quarterly stratification. The source data used in the compilation of catch and effort data was a database maintained by the OFP at a 5 degree square, month resolution. This database, known internally in the OFP as "BEST", has accumulated data from a variety of sources, processed them into a common format, and raised them so as to represent the best estimates of total catches as presented in the most recent version of the SPC Tuna Fishery Yearbook. The specifics of the source and treatment of catch and effort data in "BEST" that are relevant to the albacore assessment are as follows:

Japanese longline (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 1962–1999. These data were originally derived from logbook samples and have been raised to represent the total catch. The raising procedure, is as follows (Miyabe, pers. comm. 15 Apr 1998): "The data provided have been raised to the total statistics using raising factors calculated from total sets and sample sets submitted to NRIFSF. These raising factors are stratified by size of boats and prefecture for offshore fishery, size of boat, month and area for distant-water fishery. The area used in the raising is not so small, the raising factor applied to a certain 5x5 rectangle is the same for the same strata but different by type of fishery (offshore and distant-water fisheries) and size of boat." 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. Estimates for 2000 were assumed to be similar as 1999.

Korean longline (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 a total catch estimate (in weight) is available for 1998. The estimates for 1962–1974, 1988–1993 and 1998 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 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 (1994–1998). 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. The catches in 1999–2000 have been assumed to have the same 5 degree square, month distribution as the catches for 1994–1998, and the catches in number estimated from size composition samples collected from unloading ports mainly in Fiji. Effort is defined as "missing" for 1999 and 2000.

Miscellaneous Pacific Island longline (fishery 7). This fishery includes fleets based in Australia (east coast north of 30°S), Cook Islands, Fiji, French Polynesia, Kiribati, Marshall Islands, New Caledonia, Papua New Guinea, Solomon Islands 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.

Samoa longline (fishery 14). Catch in number and effort data by 5 degree square month have been estimated from annual landings data assuming that the monthly average distribution of vessels sampled corresponds to the monthly distribution of catch for all years. As the vessels in this fishery are mostly small, limited range alia vessels, all catch is assumed to occur in the 5 degree square nearest to the unloading port, Apia. Catches in number have been estimated from size composition samples.

NZ domestic troll (fishery 11). Estimates of catch in weight and effort by 5 degree square and month for the period 1982–1997 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 and 1998–2000, only estimates of total annual catch in weight are available. Pending the receipt of more detailed information, these catches have been assigned to the first quarter of each year and to the 5 degree square where most of the catch is known to occur. Catch in numbers was estimated using an average weight that reflects the size of fish caught in this fishery.

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 1986–1998. 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. Estimates for 1999–2000 were assumed to be similar as 1998.

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.

2.5 Length-frequency data

Available length-frequency data for each of the defined fisheries were compiled into 40 2-cm size classes (40–42 cm to 118–120 cm). Each length-frequency observation consisted of the actual number of albacore measured. Samples were not available for all fisheries for all periods. Fortunately, the MULTIFAN-CL model does not require that this be the case.

The data were collected from a variety of sampling programmes, which can be summarized as follows:

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.

Miscellaneous 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.

Samoa longline: Limited data are available from observer sampling.

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 (130 tag returns in total) were then classified by recapture fishery and recapture time period (quarter).

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 (2000). 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 sample size and the observed length-frequency 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 (2001) (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 uninformative (CV $\cong$ 0.7) Bayesian priors with low mean (0.1) were provided for each fishery.

3.3 Tag mixing

We assume that tagged yellowfin 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. 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 the third quarter of the year. 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.

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, 14 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.

Previous analyses have suggested that South Pacific albacore growth may be density dependent, i.e. that the growth rate of a particular cohort may be related to its abundance. This hypothesis has again been incorporated and tested in the present model.

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). The coefficients for the last four age classes, for which the mean lengths are very similar, are constrained to be equal for all fisheries.

Table 2. Main structural assumptions used in the yellowfin 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 (0.1). 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 during the 3rd quarter of each year. The lognormal prior for temporal variation in spatially-aggregated recruitment has a SD of 0.6, implying that recruitments of 1/3 and 3 times the average would occur about once in 25 years.
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	14 yearly age-classes, with the last representing a plus group.
Selectivity	Constant over time. Various smoothing penalties apply. Coefficients for the last **4** age-classes are constrained to be equal. Longline selectivities are non-decreasing with increasing age. Common selectivity parameters were assumed for fisheries 3 and 6 (TWLL–3 & TWLL–2) and 7 and 14 (DOM–LL & SAMOA–LL).
Catchability	Seasonal variation for all fisheries. Effort data are scaled to reflect different region sizes. 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 except the NZ troll fishery , for which SD=0.7.
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.

3.7 Catchability

Catchability was allowed to vary slowly over time (akin to a random walk) for all fisheries using a structural time-series approach. Random walk steps were taken annually, but the variance of the catchability deviations was constrained to enhance the stability of the model. The variances were specified for all fisheries as a SD or 0.10. 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, were used to model the random variation in the effort – fishing mortality relationship. For the NZ troll fishery, 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 (CV of about 0.2).

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

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 4), 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 5 for length samples aggregated over time for each fishery. Figure 5 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. The modes in the STCZ troll (fishery 12) and the driftnet (fishery 13) 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 6. The fits appear to be satisfactory, given the relatively low number of tag returns.

4.2 Tag reporting rates

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. Reporting rates for the smaller fisheries (9, 13 and 14) are relatively low as expected.

4.3 Age and growth

The estimates of mean length-at-age and the variability in length-at-age are shown in Figure 8. Also plotted on this figure for comparison are estimates of mean length for presumed annual ring counts obtained from albacore vertebrae (Labelle et al. 1996). 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. The current estimates of von Bertalanffy growth parameters are similar to those obtained from the previous MULTIFAN-CL analysis of albacore data (Fournier et al. 1998). The estimate of K is slightly lower (0.12 cf. 0.19 yr^{-1}) and the estimate of L_∞ is marginally higher (112.0 cf. 107.2 cm).

4.4 Selectivity

The selectivity coefficients (Figure 9) reflect the age-specific exploitation characteristics of each fishery. Albacore appear to be fully recruited to the longline fisheries by about age 10. There is considerable heterogeneity in selectivity for the NZ domestic troll (fishery 11) and the STCZ troll (fishery 12) fisheries, even though few larger albacore are caught by these fisheries. The high selectivity for older fish reflects the low population of these age classes in the southern region.

4.5 Catchability

We assumed independent catchability amongst all the fisheries. There are several time-series changes in the estimated catchability (Figure 10). 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. By contrast, the trends for the Taiwanese longline fishery in the central and southern regions are relatively flat, suggesting a consistent targeting strategy towards albacore. Seasonal catchability is a feature in most of the fisheries.

The overall consistency of the model with the observed effort data 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 extracted all the information present in the data regarding catchability variation.

4.6 Natural mortality

The natural mortality rate is estimated to be about 0.4 yr^{-1} for juvenile albacore, with an increase to about 1.0 yr^{-1} beginning at around the size of 100 cm (Figure 12). Prior to this size, the sex ratio of albacore has changed 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 the mid-1970s. The lower recruitments during the 1980s were then followed by some increase during the early 1990s. We might speculate on possible environmental variation associated with these patterns, however a detailed analysis has not yet been carried out. The most recent recruitment estimates are considerably higher than average, though they are relatively imprecise compared to historical estimates.

The precision of the total recruitment estimates (Figure 14) is indicated by the approximate 95% confidence intervals. For the whole period considered by the model, the confidence intervals are larger from 1960 to 1980 and during the last three years of the time-series (1998–2000).

4.9 Biomass trends

Time-series trends in total 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. Note that biomass is fairly equally distributed between the central and southern regions with a very small proportion occurring in the northern region. The estimated biomass ratio of the last three years to the first three years of the time period is around 60%.

4.10 Fishing mortality and the impact of fishing

Estimates of weighted average annual fishing mortality rates for juvenile (age classes 1–5) and adult (age classes 6–14) albacore are shown in Figure 16. There was a spike in juvenile fishing mortality in the late 1980s associated with the driftnet fishery. Longline fishing mortality rates have increased strongly since the mid-1980s.

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 south Pacific are shown in Figure 15. A small impact occurs in the northern region; however there are less fish in this region relative to the other regions. There is little evidence for significant fishery depletion in the central and southern regions.

5 Conclusions

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

1. The model produces a consistent interpretation of the length-frequency data that is coherent with previous estimates of age and growth from analysis of vertebral rings.
2. Estimates of natural mortality rates are consistent with those obtained from analyses of tagging data alone. The pattern of age and size-specific variation in natural mortality is

strongly related to changes in sex ratio with size, which may suggest an effect of reproductive activity on female natural mortality.

3. The recruitment pattern is similar to previous analyses in having a marked downwards shift in the mid- to late 1970s. The lower recruitments during the 1980s were then followed by some increase during the early 1990s. Estimates of recruitment estimates in recent years are considerably higher than average, though they are relatively imprecise.
4. Biomass trends are largely driven by the recruitment, showing a decline through the late 1980s, followed by an increase. Most of the population is distributed in the southern and central regions.
5. The fishing mortality estimates are low for both adult and juvenile age classes. This is probably a reflection of the low observed recovery of tagged albacore. However, running the analysis without the tagging data did not significantly alter the results. It is unlikely that fishing mortality is underestimated to such an extent that overfishing could be currently occurring.

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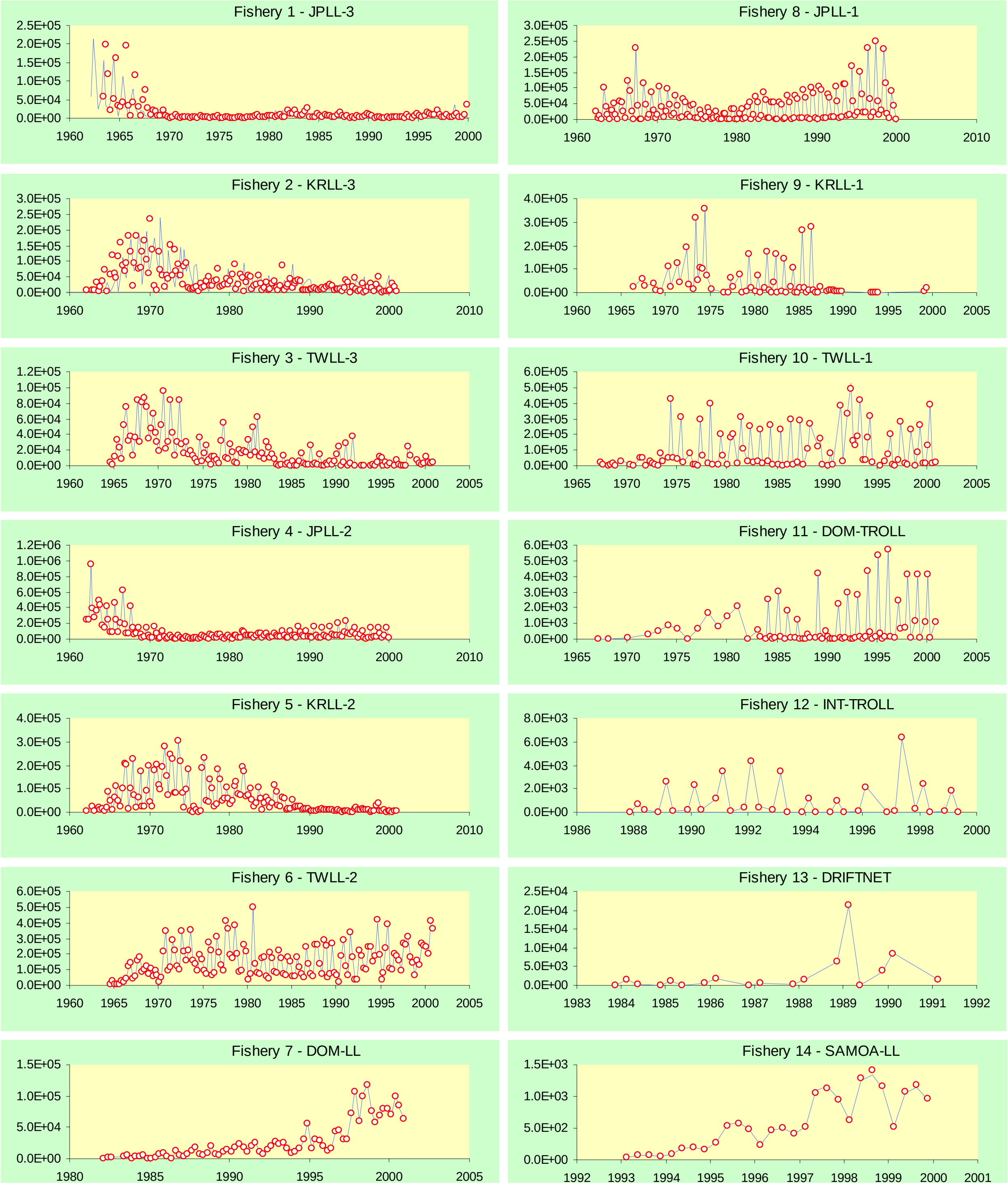

Figure 4. Observed (circles) and predicted (lines) total catches by time period for each fishery.

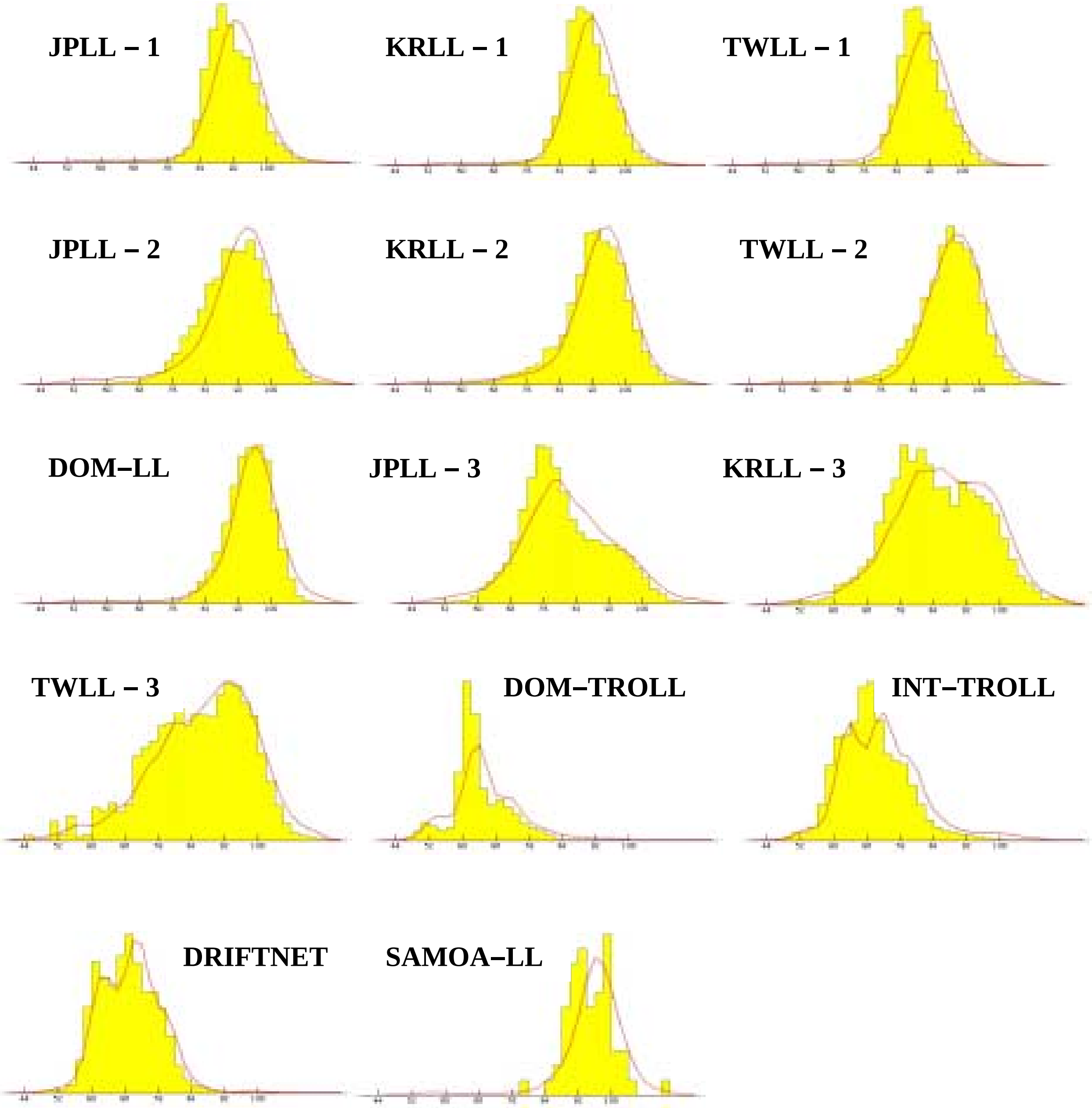

Figure 5. Observed (yellow histograms) and predicted (red lines) length-frequency data aggregated over time for each fishery.

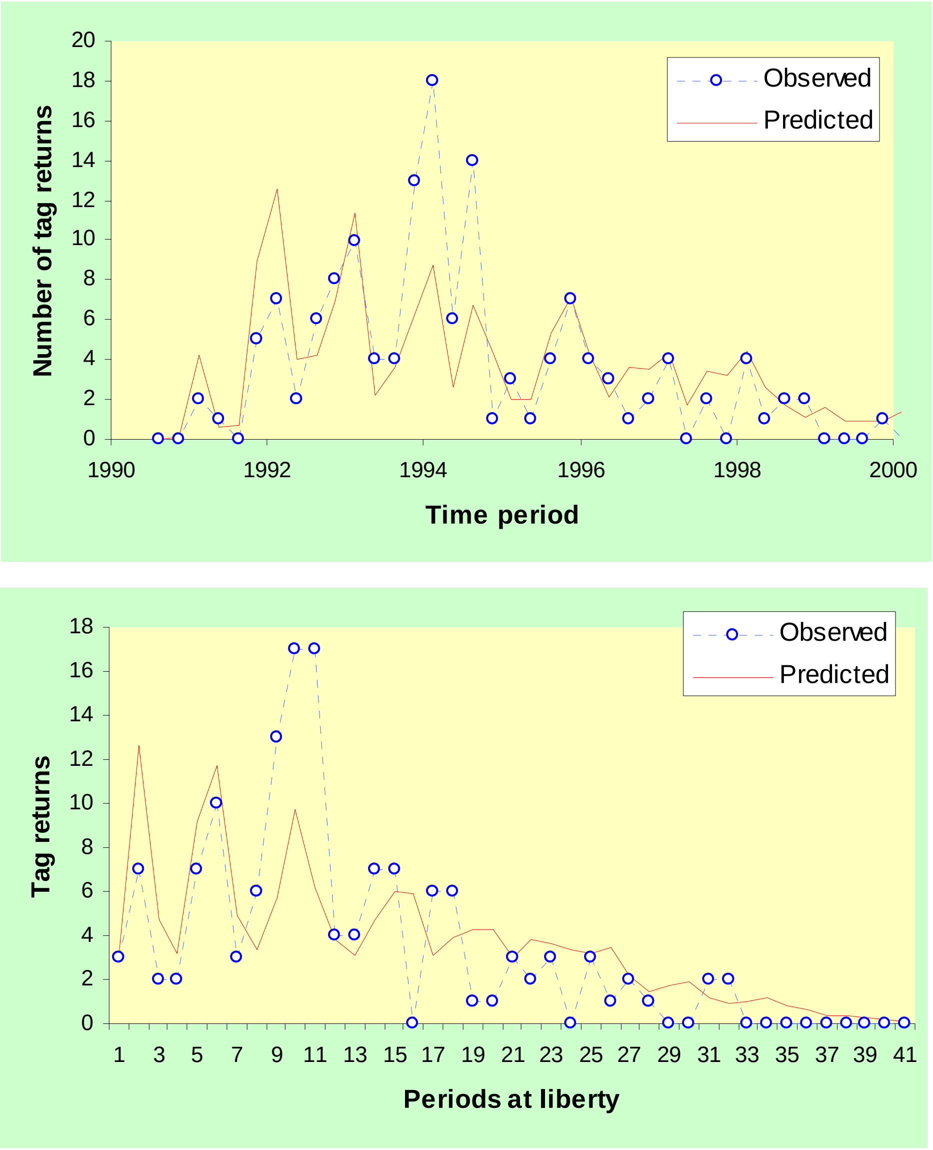

Figure 6. Observed (red dots) and predicted (blue lines) tag returns by time period (upper panel) and by periods at liberty (lower panel).

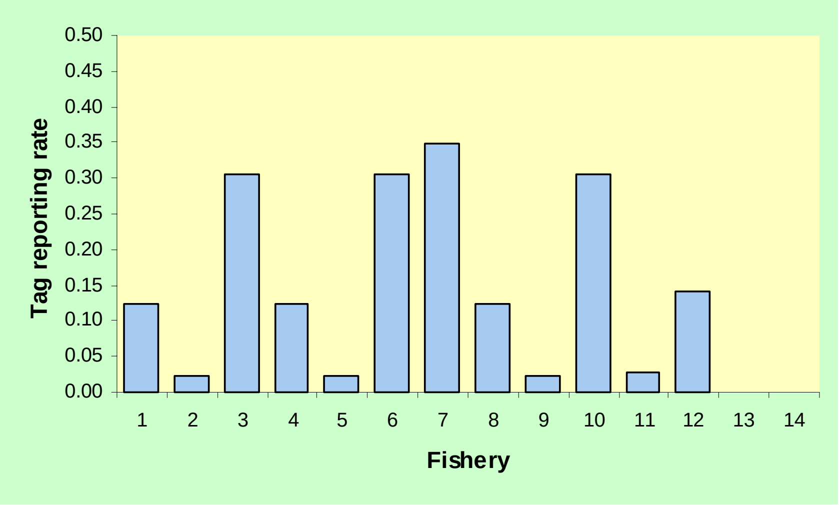

Figure 7. Estimates of tag reporting rates by fishery. Priors for all fisheries were 0.1 with a range from 0 to 0.8.

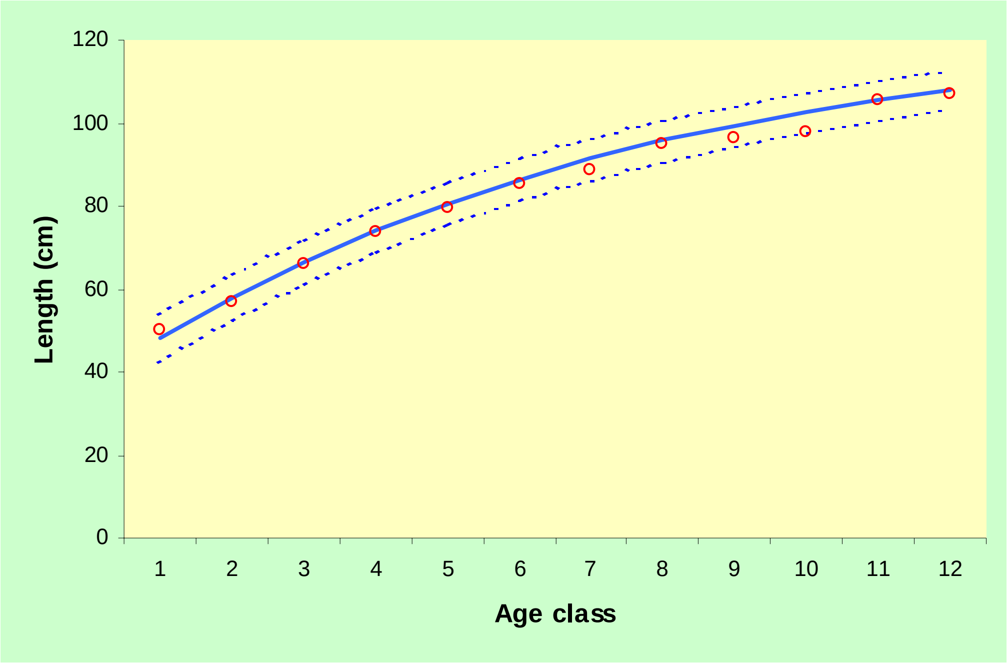

Figure 8. Estimated mean lengths-at-age for albacore tuna (thick line). The thin lines are plus and minus 2 standard deviations in length-at-age and are indicative of the estimated length range of each age class. The red circles are mean lengths-at-age (age class 1 = 2 years) estimated from vertebral ring counts (Labelle et al. 1996).

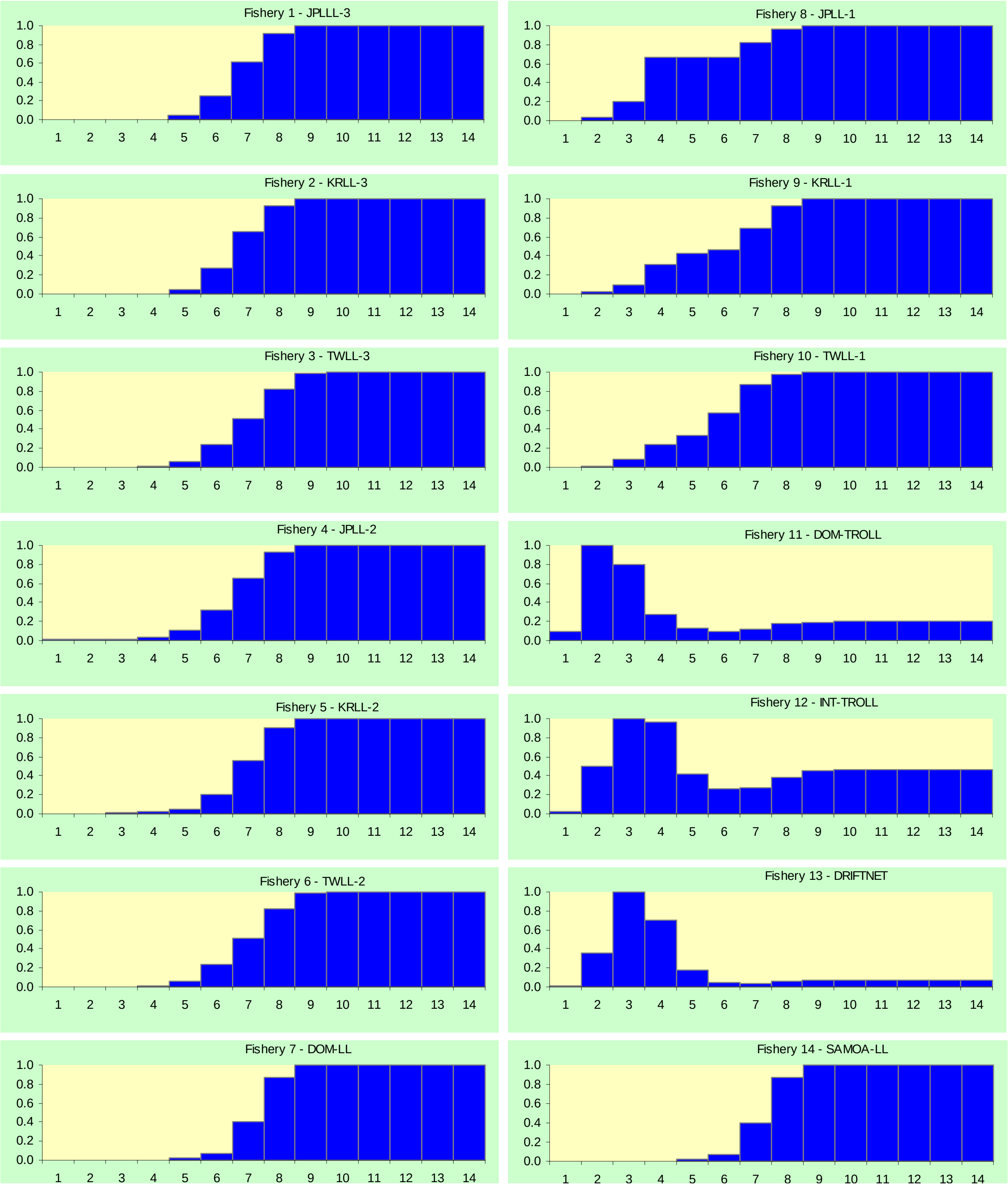

Figure 9. Estimated albacore tuna selectivity coefficients, by fishery.

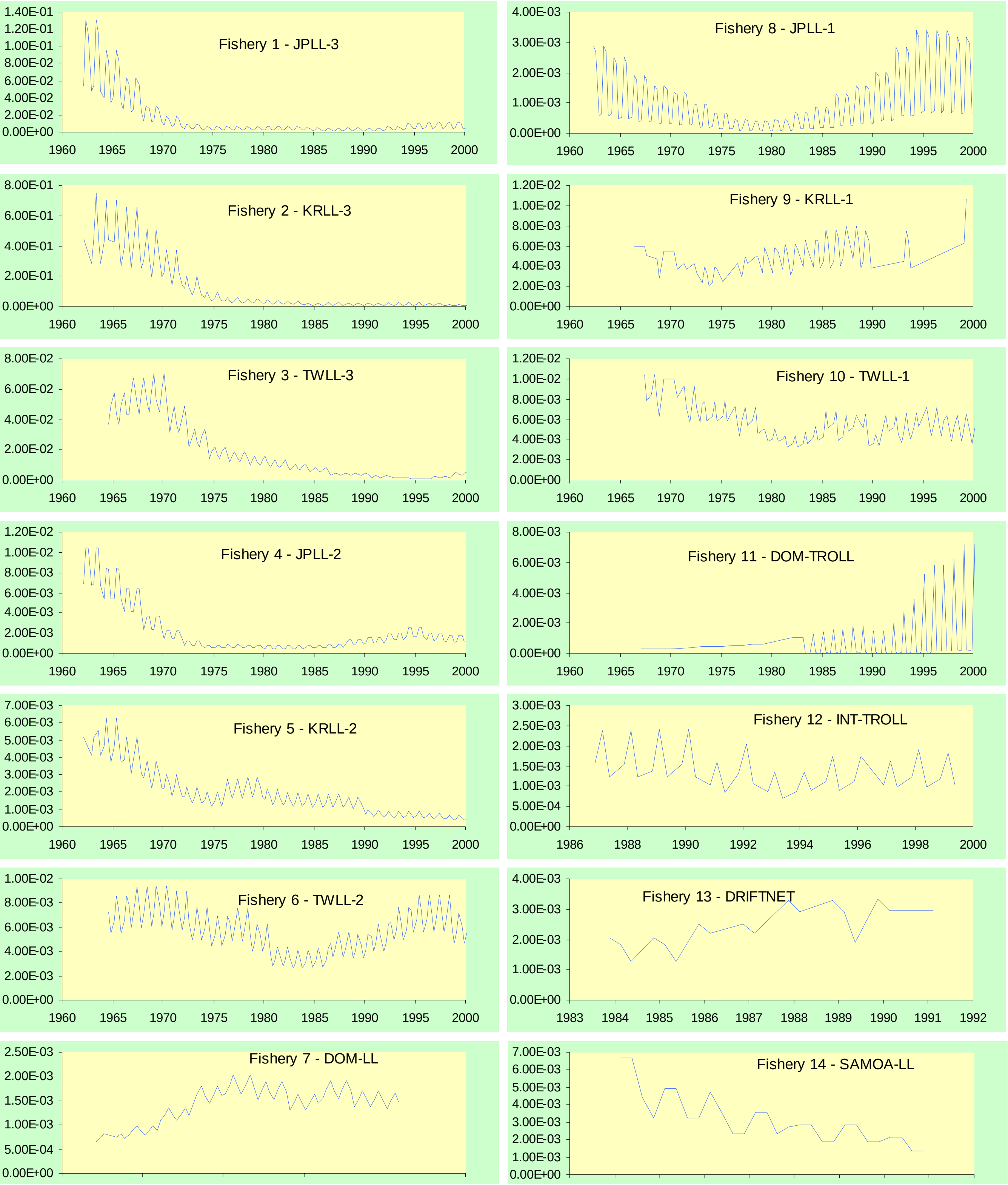

Figure 10. Estimated catchability time series (lines) and the catchability plus effort deviations (open circles).

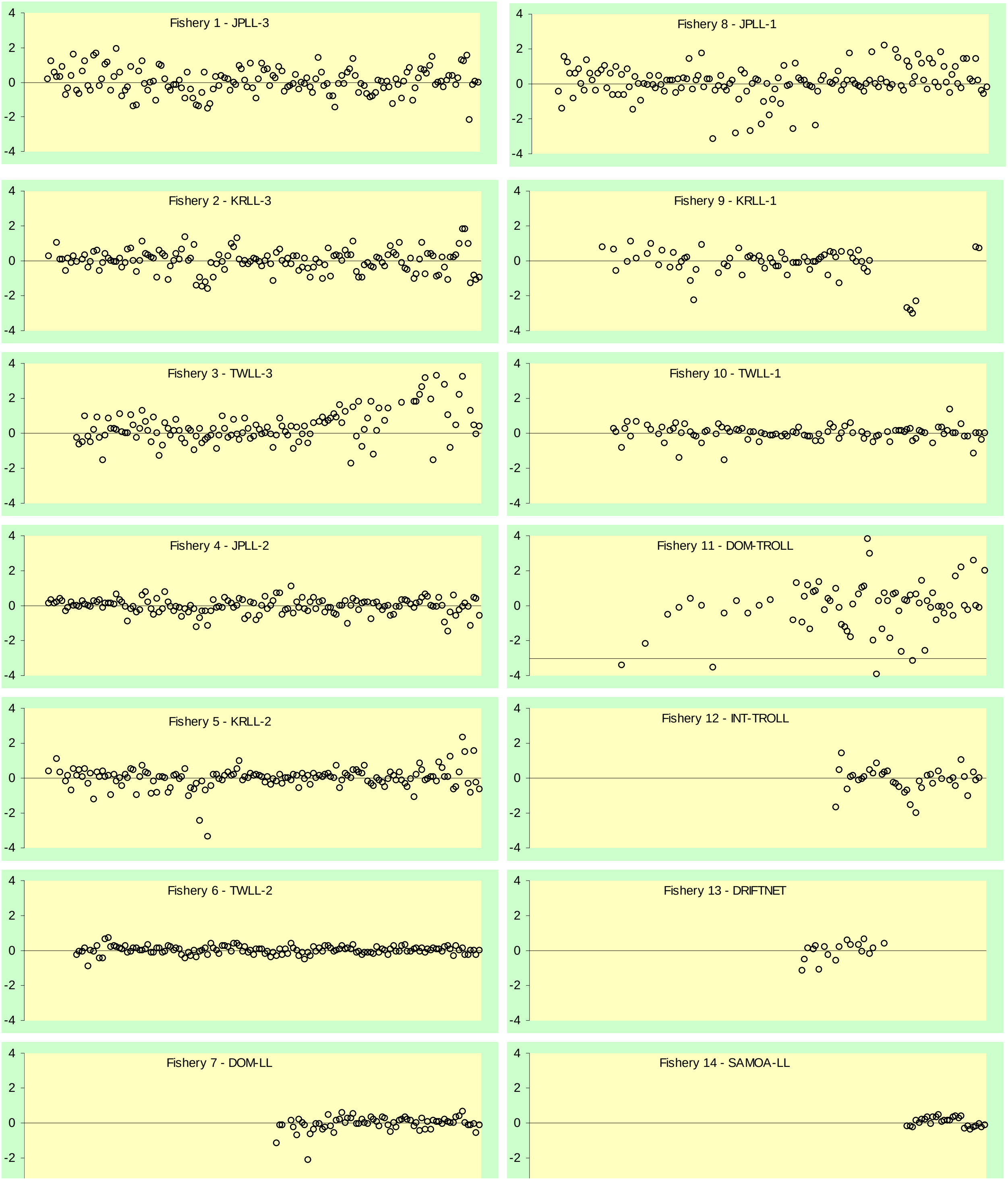

Figure 11. Effort deviations by time period for each fishery.

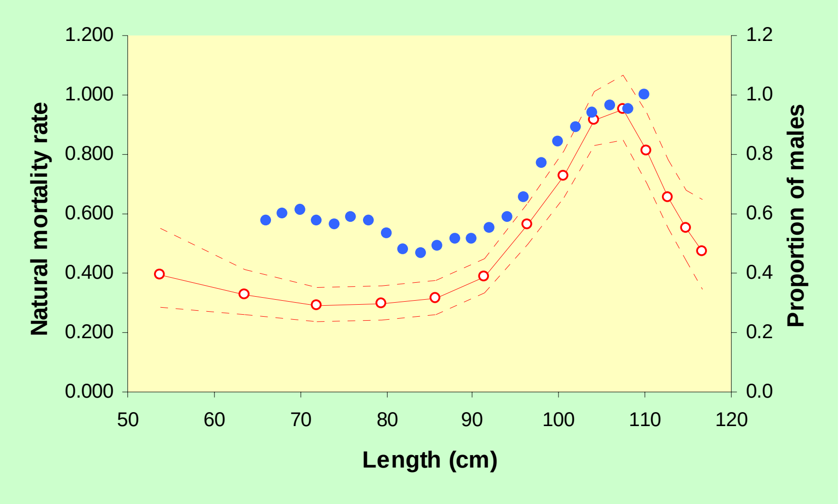

Figure 12. Estimated natural mortality rates (annual) and approximate 95% confidence intervals for each age-class plotted against the mean length of each age-class. The blue dots are the observed proportions of male albacore (by 2 cm size class, 5 class smoother).

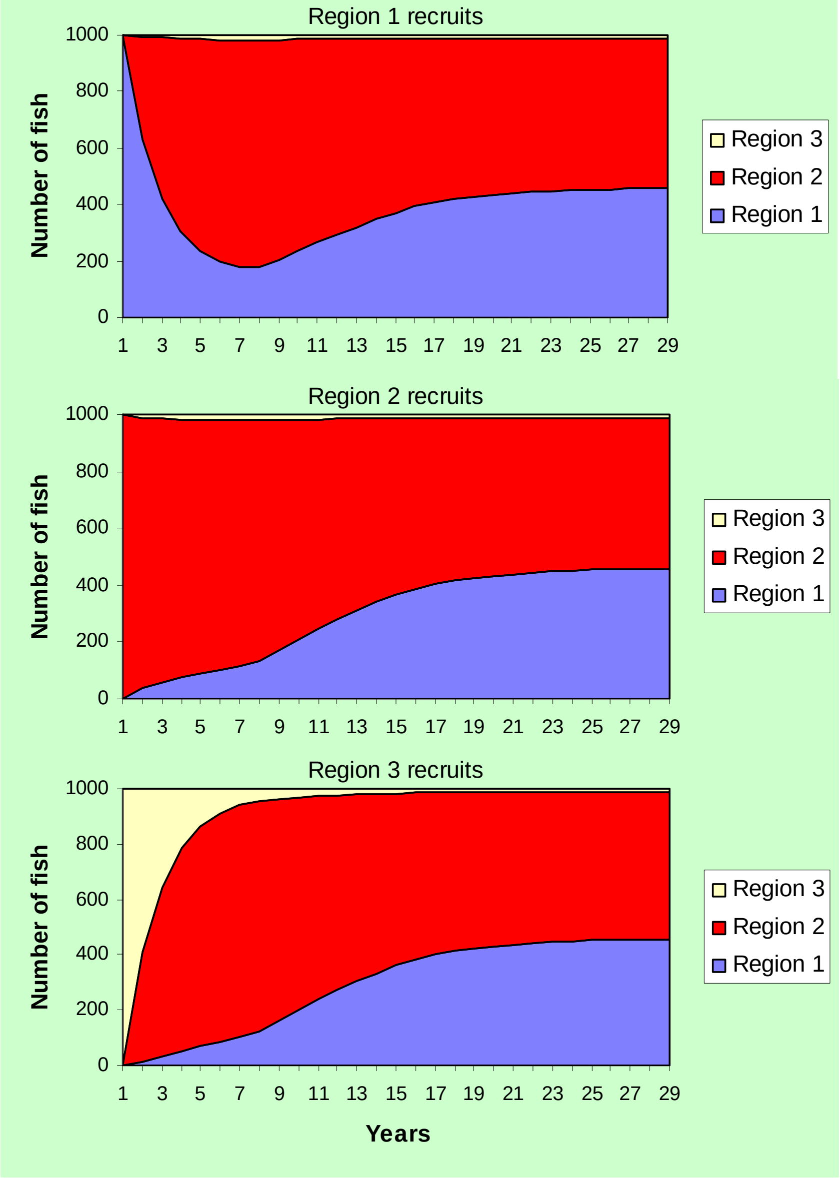

Figure 13. A representation of the estimated movement coefficients for albacore tuna. In each panel, the estimated relative distribution (by region) of a cohort of 1,000 recruits originating in a specific region is plotted by quarter.

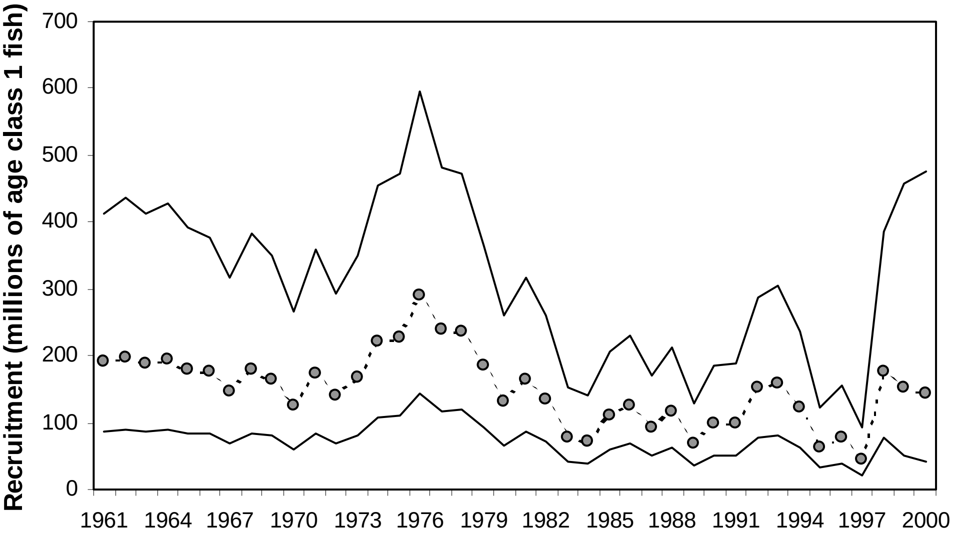

Figure 14. Estimated annual recruitment, with approximate 95% confidence intervals.

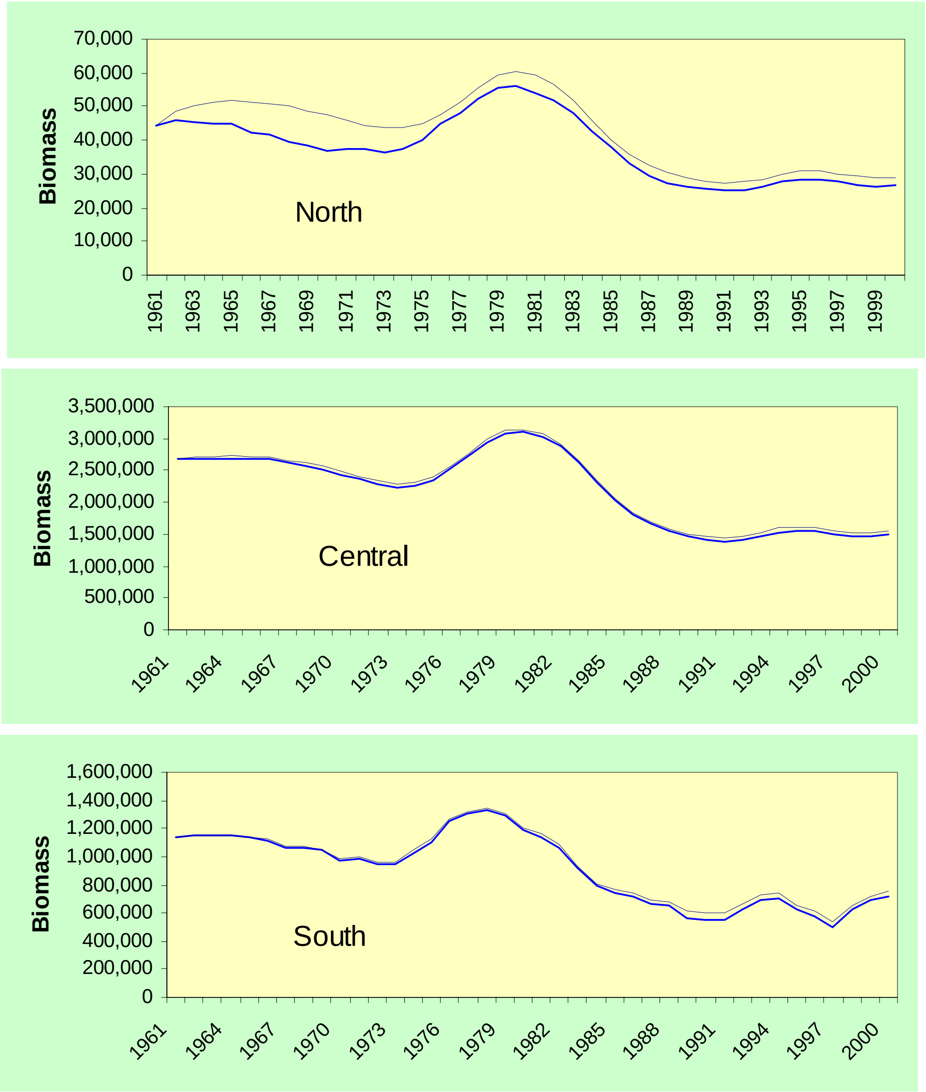

Figure 15. Comparison of the estimated biomass trajectories (lower heavy lines) with biomass trajectories that would have occurred in the absence of fishing (upper thin lines) for the base-case model.

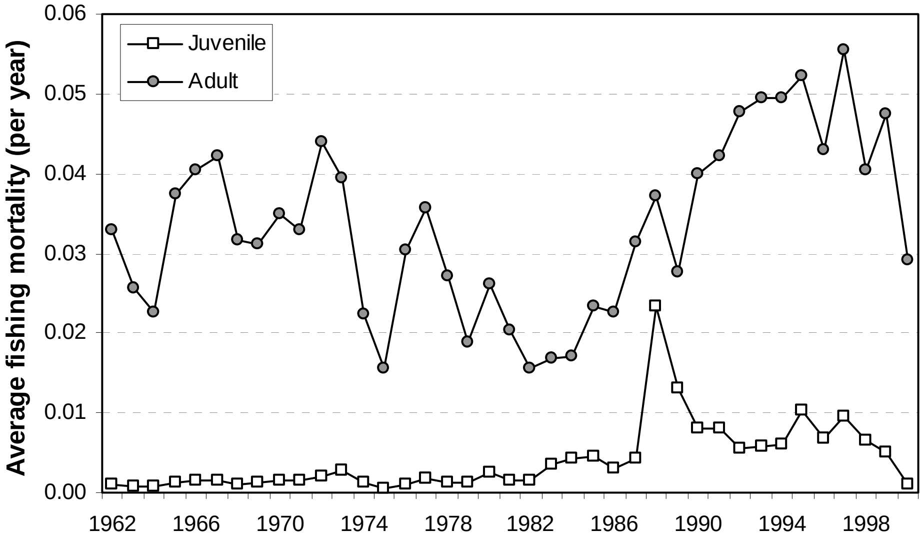

Figure 16. Estimates of average annual fishing mortality for juvenile and adult age classes.