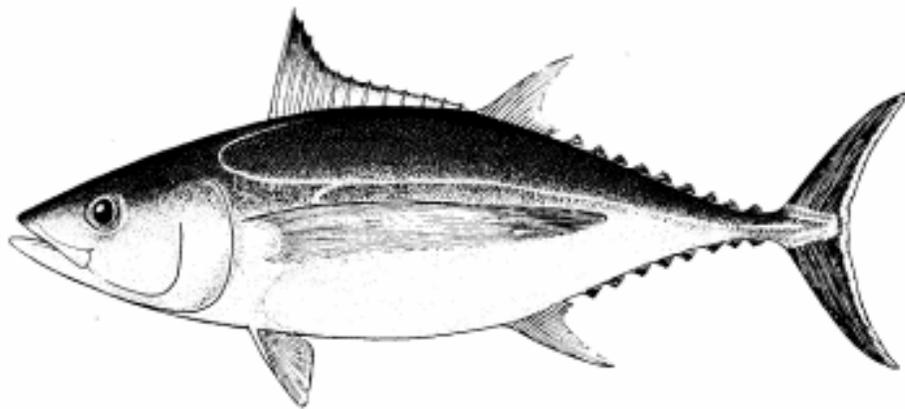




Stock assessment of albacore tuna in the south Pacific Ocean



Adam Langley and John Hampton

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

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1 Introduction

This paper presents the current stock assessment of albacore tuna (*Thunnus alalunga*) in the south Pacific Ocean (east of 110°W). The overall objectives of the assessment are to estimate population parameters, such as time series of recruitment, biomass and fishing mortality, that indicate the status of the stock and impacts of fishing. We also summarise the stock status in terms of well-known reference points, such as the ratios of recent stock biomass to the biomass at maximum sustainable yield (B/B_{MSY}) and recent fishing mortality to the fishing mortality at MSY (F/F_{MSY}). The methodology used for the assessment is that commonly known as MULTIFAN-CL (Fournier et al. 1998; Hampton and Fournier 2001; Kleiber et al. 2003; <http://www.multifan-cl.org>), which is software that implements a size-based, age- and spatially-structured population model. Parameters of the model are estimated by maximizing an objective function consisting of both likelihood (data) and prior information components.

2 Background

2.1 Biology

Albacore tuna comprise a discrete stock in the South Pacific Ocean (Murray 1994). Mature albacore (greater than 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 one year later, at a size of 45–50 cm in 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. These seasonal migrations have been inferred from monthly trends in catch rates from the longline fisheries in the subequatorial region (Langley 2004). Catch rates in the subequatorial waters peak in December–January and May–July indicating a southern migration of albacore during early summer and a northward movement of fish during winter. This movement tends to correspond to the seasonal oscillation of the location of the 23–28° C isotherm of sea surface temperature.

A recent age study of south Pacific albacore, based on daily growth increments on the otolith, indicate initial growth is rapid, achieving a length of 45–50 cm (F.L.) in the first year (Leroy & Lehodey 2004). Subsequent growth is slower, approximately 10 cm per year from ages 2 to 4 and declining in a classic von Bertalanffy fashion thereafter (Labelle et al. 1993). Maximum recorded length is about 120 cm (FL).

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.

2.2 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 geographic range (Figure 2). In recent years, the longline catch 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 operated 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 (Figure 3). Longline fisheries operate throughout the year although there is a strong seasonal trend in the distribution of the catch with the fishery operating in the southern latitudes (south of 35° S) during late summer and autumn and moving northwards during winter (Figure 3).

After an initial period of development, annual catches of South Pacific albacore varied considerably and catches are now about 60,000 mt (Figure 4). Longline gear accounts for most of the catch, about 30,000 mt per year on average prior to about 1998. The increase in longline catch to approximately 50,000 mt in 2001 is largely due to the development of small-scale longline fisheries in Pacific Island countries. Troll catches are relatively small, generally producing less than 10,000 mt per year. The driftnet catch reached 22,000 mt in 1989, but has since declined to zero following a United Nations moratorium on industrial-scale driftnetting.

3 Data compilation

The data used in the South Pacific albacore assessment consist of fishery-specific catch, effort and length-frequency data and tag release-recapture data. The details of these data and their stratification are described below.

3.1 Spatial stratification

The geographic area encompassed in the assessment is the Pacific Ocean south of the equator from 140°E to 110°W (Figure 2). This area includes almost all the catch of albacore from the south Pacific Ocean. Previous stock assessments of south Pacific albacore have stratified this area into three latitudinal bands (Fournier et al. 2001, Hampton 2003, Labelle & Hampton 2004). This stratification was defined to account for the distinctive size segregation by latitude, with the smallest fish being found in southern waters.

For the current assessment, the spatial stratification was investigated via qualitative and statistical analysis (Helu 2004). The criteria for defining an individual stratum was consistency in the seasonal and temporal trends in albacore catch rate from the main constituent longline fisheries within an area, while retaining the separation of the northern and southern areas to account for the differences in the size of fish caught by the longline fisheries. In establishing stratum boundaries, consideration was also given to the spatial distribution of the operation of the main domestic longline fisheries, thereby, allowing the results of the assessment to be more directly applicable to the local scale management of these fisheries.

Based on the criteria described above, the stock assessment area was divided into four separate strata delineated by latitude 30°S and longitude 180° (Figure 2). These strata were used to define the individual fisheries (see Section 3.3) and define the regions of the model structure. However, due to uncertainties regarding the parameterisation of movement of albacore between the regions (see Section 5.1), the regional structure of the model was rejected and a single region model was adopted that retained the original fishery definitions (based on the four regions).

3.2 Temporal stratification

The time period covered by the assessment is 1952–2003. Within this period, data were compiled into quarters (Jan–Mar, Apr–Jun, Jul–Sep, Oct–Dec). The assessment was not extended to

include data from the 2004 fishery due to delays in the provision of catch and effort data from the Taiwanese fleet – a key component of the fishery and input to the assessment.

3.3 Definition of fisheries

MULTIFAN-CL requires the definition of “fisheries” that consist of relatively homogeneous fishing units. Ideally, the fisheries are defined to have selectivity and catchability characteristics that do not vary greatly over time. For most pelagic fisheries assessments, fisheries can be defined according to gear type, fishing method and region. However, for the south Pacific albacore fishery, not all longliners of a particular type or nationality target albacore and some fleets have changed their targeting practices over time. Therefore, some additional stratification of longliners into national fleets was deemed necessary to capture the variability in fishing operations with respect to albacore.

The stratification of the longline fishery was extended by defining a separate fishery for each of the main domestic longline fisheries. These fisheries operate in relatively discrete areas and differ in magnitude and species composition of the catch. The fisheries have also commenced at different times and have exhibited different seasonal and temporal trends in the catch rate of albacore. This additional stratification also increases the utility of the assessment by generating results that are relevant to the management of the individual domestic fisheries.

A total of 23 fisheries were defined for the assessment, including 19 separate longline fisheries, two driftnet fisheries, and two troll fisheries (Table 1). The longline fisheries were comprised of a composite Japan/Korea longline fishery in each of the four regions (4), a Taiwanese longline fleet in each region (4), the domestic fleets of New Caledonia, Fiji, New Zealand, Tonga, Samoa and American Samoa combined, and French Polynesia (6), the domestic fishery of Australia in two regions (2), and the remaining longline data from three regions (3). Separate troll and driftnet fisheries were defined for the two southern regions of the assessment area. The geographic distribution of the cumulative catch from each fishery is presented in Figure 5.

3.4 Catch and effort data

Catch and effort data were compiled according to the fisheries defined in Table 1. All catches were expressed in numbers of fish, with the exception of the driftnet fishery for which catches in weight (tonnes) were used. For the longline fisheries, effort was expressed in hundreds of hooks, while for the troll and driftnet fisheries, the number of vessel days of fishing activity was used. For each fishery, data were aggregated by quarterly temporal strata.

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:

Japanese longline (fisheries 1, 7, 13, 17). Catch and effort data have been provided by the National Research Institute of Far Seas Fisheries (NRIFSF) at 5 degree square, month resolution for 1952–2003. 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.

Korean longline (fisheries 1, 7, 13, 17). 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 1998–2003. The estimates for 1962–1974, 1988–1993 and 1998–2003 have been converted to 5-degree square by 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 were also 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 1998–2003, 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 1998–2003 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.

The catch and effort data from the Japanese and Korean fleets were combined to derive a composite fishery in each of the four regions.

Taiwanese longline (fisheries 2, 8, 14, 18). 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 (1994–2003). 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. Since this fishery targets mainly albacore, the analytical procedure relies heavily on the Taiwanese CPUE trend for assessment purposes.

Domestic longline fleets (fisheries 3–6, 9–12, 15, 16). Separate longline fisheries were defined for each of the main domestic longline fisheries operating in the south Pacific, specifically the domestic fleets of New Caledonia, Fiji, New Zealand, Tonga, Samoa and American Samoa combined, and French Polynesia and the domestic fishery of Australia apportioned between two regions. Logbook data submitted by these countries to the OFP were aggregated into 5 degree square, month format and raised to estimates of their total annual catches. Most of these fisheries commenced in the late 1980s or early 1990s. The remainder of the longline data, usually from smaller domestic longline fleets (e.g. Cook Islands, Vanuatu, Papua New Guinea, Solomon Islands) were compiled into separate fisheries in regions 1, 2, and 4.

NZ domestic troll (fishery 20). Estimates of catch in weight and effort by 5 degree square and month for the period 1982–2003 have been provided by the New Zealand Ministry of Fisheries. 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 quarter 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 1986–2003. Likewise, data for New Zealand vessels has been provided 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 (net length in km) 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. The coverage of the entire South Pacific driftnet fishery represented by these data is unknown but is likely to be high during 1983–1991.

A summary of the catch per unit effort (CPUE) is given in Figure 7.

3.5 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 as follows:

Japanese, Korean and Taiwanese longline (fisheries 1, 2, 7, 8, 13, 14, 17 & 18): 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.

Domestic longline fleets (fisheries 3–6, 9–12, 15, 16 & 19): 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. Length frequency data are available for most of these fisheries, with the exception of the two Australian longline fisheries (fisheries 3 and 15).

NZ domestic troll (fishery 20): Data have been collected from port sampling programmes conducted by the Ministry of Fisheries and, more recently, NIWA.

STCZ troll (fishery 21): Length-frequency data have been collected by port sampling programmes in Levuka (Fiji), Pago Pago (American Samoa) and Papeete (French Polynesia), and, during 1990–1991 and 1991–1992, by scientific observers.

Driftnet (fisheries 22 & 23): 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.

For each fishery, the temporal coverage of length frequency sampling is presented in Figure 8. No length samples were available from the fishery prior to 1962. For a number of fisheries, sampling

has been negligible, while for other fisheries the duration of sampling coverage has been limited relative to the operation of the fishery. Nevertheless, for the long-standing Japan/Korea longline fisheries and the Taiwanese longline fisheries, length samples are available from the early 1960s onwards (Figure 8).

For the northern regions (1 and 2), the catches were principally comprised of large albacore (80–110 cm FL), while smaller fish comprise a high proportion of the catch from the southern regions (regions 3 and 4) (Figure 9). For each of the main fisheries, there was a general increase in the length of fish in the catch from the 1960s to the early 1990s (Figure 9). The size composition of the catch remained relatively stable in the subsequent period.

3.6 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 austral summers of 1990–1992 and from an earlier programme in the 1980s involving members of the South Pacific Albacore Research Group (Figure 10). Tags were released using standard tuna tagging equipment and techniques by trained scientists and scientific observers. In 1990–1991, 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 14 tag release groups (year/quarter). The returns from each size class of each tag release group (138 tag returns in total) were then classified by recapture fishery and recapture time period (quarter).

The tag releases were principally comprised of juvenile fish (age 1–4 years) and few fish larger than 80 cm (FL) were tagged (Figure 11). The length composition of fish from the tag recoveries was comparable to the length at release, albeit slightly larger allowing for growth during the period at liberty. Many (57%) of the tag recoveries were from the longline fisheries in the southern regions (3 and 4), in particularly fishery 18 (Figure 11). The Taiwanese longline fishery in region 2 also accounted for a relatively high proportion of all tag returns (20%). A few tags were also returned from the two troll fisheries. Most of the tag recoveries occurred during the five years following the peak in releases during the early 1990s (Figure 10).

3.7 Biological parameters

The biological parameters included in the model are presented in Table 2. Albacore are assumed to reach maturity at age five years of age and be fully mature at age six years. The length-weight relationship is derived from estimated from available length-weight data (Hampton 2002). The von Bertalanffy growth parameters are provided as initial starting values in the model. Similarly, an initial value of 0.4 is assumed for natural mortality (over all age classes) and subsequently estimated during the fitting procedure.

4 Model description – structural assumptions, parameterisation, and priors

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 3.

4.1 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 Poisson distribution. Previous analyses had assumed a negative binomial error structure; however, the negative binomial distribution approximates the Poisson error structure when the variance is estimated to be high. On this basis, it wasn't considered to be worthwhile estimating the additional parameters associated with the negative binomial.

4.2 Tag reporting

Tag-reporting rates are estimated 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. This is reflected in the uninformative priors for all fisheries (mean of 0.1, stdev = 0.7). The maximum reporting rate (for the various fisheries) was set to 0.9. 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 could also be immediate mortality due to tagging.

Tag reporting rates were assumed to be equivalent for the four Taiwanese longline fisheries and for the four Japan/Korea longline fisheries.

4.3 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.

4.4 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 regions of the model domain, with the proportion of total recruitment shared equally between the two southern regions. However, this assumption was only relevant in the four region model and was not applicable to the single region model. In the single region model, new recruits are available to all fisheries mediated by the age-specific selectivity of the individual fisheries.

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 July. The time-series variation in recruitment was somewhat constrained by a log-normal 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 be related to spawning biomass according to the Beverton-Holt stock-recruitment relationship (SRR). The SRR was incorporated mainly so that a yield analysis could be undertaken for stock assessment purposes. A relatively weak penalty was applied to deviation from the SRR so that it would have only a slight effect on the recruitment and other model estimates (Hampton and Fournier 2001, Appendix D).

Typically, fisheries data are very uninformative about SRR parameters and it is generally necessary to constrain the parameterisation to have stable model behaviour. A beta-distributed prior was used for the “steepness” coefficient (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 = 0.1 ($a = 10$, $b = 2$). In other words, the 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%).

4.5 Age and growth

The assumptions made concerning age and growth in the MULTIFAN-CL model are (i) the lengths-at-age are normally distributed for each age class; (ii) the mean lengths at age follow a von Bertalanffy growth curve; (iii) the standard deviations in length-at-age is a linear function of the mean length-at-age. For any specific model, it is necessary to assume the number of significant age-classes in the exploited population, with the last age-class being defined as a “plus group”, i.e. all fish of the designated age and older. This is a common assumption for any age-structured model. For the results presented here, 20 annual age classes are used; however an alternative assumption of only 12 age classes was explored via a sensitivity analysis and shown to have little impact on the model results.

4.6 Selectivity

Selectivity is fishery-specific and assumed to be time-invariant and length-based. The selectivities at age were estimated using a cubic spline parameterisation. Each selectivity function was parameterised with four nodes allowing considerable flexibility in the functional form while minimizing the number of parameters required to be estimated.

Limited length frequency data were available for a number of fisheries and the selectivities for these fisheries were assumed to be equivalent to other fisheries of the same method operating within the same region. Specifically, the Australian and New Caledonia longline fisheries in

region 1 and Australian and New Zealand longline fisheries in region 3 shared common selectivity, while a single selectivity was assumed for the drift-net fisheries in regions 3 and 4.

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. There was no age-specific constraint on the formulation of the selectivity functions for the troll and drift net fisheries which principally catch juvenile albacore, with the exception that the selectivity of the last two age classes was equivalent for all fishery-specific selectivities.

4.7 Catchability

Catchability was assumed to be constant over time for all four TWLL fisheries. This assumption was based on the fact that these fisheries have consistently targeted albacore 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 0.1 on a log scale. Seasonal variation in catchability was also allowed for to explain the strong seasonal variability in CPUE for most of the fisheries.

4.8 Effort variability

Effort deviations, constrained by prior distributions of zero mean and variance equivalent to a CV of about 0.2 (log scale) were used to model the random variation in the effort – fishing mortality relation. The individual effort observations were weighted scaled by the square root of the effort.

The sensitivity of the model to the influence of the effort series was examined by increasing the penalty weight on the effort deviations prior.

4.9 Movement

In previous assessments, seasonal (and age dependent) movement has been estimated. However, the resulting movement coefficients appear to be inconsistent with the other observations from the fishery. For example, the estimated movement of fish northward during the first and last quarters of the year (Labelle & Hampton 2003) is contrary to the southern operation of the fishery during the austral summer. Given the limited number of tag releases and recoveries and the localized area of tag release, it is not surprising that the tagging data is uninformative regarding the seasonal movement of albacore.

An important component of the four region model was to formulate the movement dynamics that represent the average seasonal movement of albacore. In the absence of sufficient tagging data, it was decided to determine movement coefficients (externally of the model) that reflect the main observations from the fishery, principally the seasonal trends in albacore CPUE in the domestic fisheries operating in the subequatorial region. These fisheries typically exhibit strong seasonal fluctuations, with high catch rates in the early summer (December–January) and winter (May–July). During the remainder of the year, catch rates are approximately half the level achieved during these period. On this basis, a schedule was derived that moves 50% of the albacore (all age classes) from the northern regions (1 and 2) at the start of the first quarter and corresponding shift of fish northward at the start of the third quarter. Limited southward/northward movement occurred during the intervening periods. Similarly, the schedule included limited east/westward movement in all quarters.

The movement schedule used in the four region model is depicted in Figure 12 and Figure 13. These movements were fixed during the initial phases of the fitting procedure and then allowed to be estimated. Movement coefficients were constant over all age classes.

For comparison with previous analyses, two additional sensitivities were conducted for the four-region model, whereby, non age-specific movement was estimated with and without the estimation of seasonal trends in catchability for all fisheries.

The sensitivity of the model to assumptions regarding the regional structure were also examined by comparing the results from the four-region model with a model that combined all the regions (single-region model) while maintaining the equivalent fisheries structure.

4.10 Natural mortality

Natural mortality was set at an initial value of 0.4 for all age classes and estimated during the fitting procedure assuming an uninformative prior (mean = 0.4 with no penalty).

4.11 Initial population

The population was assumed to be at equilibrium in the first year of the model (1952) and the initial age structure is determined as a function of the estimated value of natural mortality.

Preliminary model runs (not reported in detail in this report) compared the effect of commencing the model in 1960 and determining the initial age structure as a function of total mortality (natural mortality and fishing mortality) averaged over the first five years of the assessment period. However, this approach resulted in very high initial exploitation rates on the age classes vulnerable to the longline fishery. This observation appears to be inconsistent with the level of total catch taken by the longline fleet prior to 1960 and, consequently, this approach was discarded in favour of the model commencing in 1952.

4.12 Parameter estimation

The parameters of the model were estimated by maximizing the log-likelihoods of the data plus the log of the probability density functions of the priors and smoothing penalties specified in the model. The maximization was performed by an efficient optimization using exact derivatives with respect to the model parameters. Estimation was conducted in a series of phases, the first of which used arbitrary starting values for most parameters. Some parameters were assigned specified starting values consistent with available biological information.

The Hessian matrix computed at the mode of the posterior distribution was used to obtain estimates of the covariance matrix, which was used in combination with the Delta method to compute approximate confidence intervals for parameters of interest.

4.13 Stock assessment interpretation methods

Several ancillary analyses are conducted in order to interpret the results of the model for stock assessment purposes. These methods involved are summarized below and the details can be found in Kleiber et al. (2003). Note that, in each case, these ancillary analyses are completely integrated into the model, and therefore confidence intervals for quantities of interest are available using the Hessian-Delta approach (or likelihood profile approach in the case of yield analysis results).

4.13.1 Fishery impact

Many assessments estimate the ratio of recent to initial biomass as an index of fishery depletion. The problem with this approach is that recruitment may vary considerably throughout the time series, and if either the initial or recent biomass estimates (or both) are “non-representative” because of recruitment variability, then the ratio may not measure fishery depletion, but simply reflect recruitment variability.

We approach this problem by computing biomass time series using the estimated model parameters, but assuming that fishing mortality was zero. Because both the *real* biomass B_t and the *unexploited* biomass B_{0t} incorporate recruitment variability, their ratio at each time step of the analysis $\frac{B_t}{B_{0t}}$ can be interpreted as an index of fishery depletion.

4.13.2 Yield analysis and projections

The yield analysis consists of computing equilibrium catch (or yield) and biomass, conditional on a specified basal level of age-specific fishing mortality (F_a) for the entire model domain, a series of fishing mortality multipliers, $fmult$, the natural mortality (M), the mean weight-at-age (w_a) and the SRR parameters α and β . All of these parameters, apart from $fmult$, which is arbitrarily specified over a range of 0–50 in increments of 0.1, are available from the parameter estimates of the model. The maximum yield with respect to $fmult$ can easily be determined and is equivalent to the MSY. Similarly the total and adult biomass at MSY can also be determined. The ratios of the current (or recent average) levels of fishing mortality and biomass to their respective levels at MSY are of interest as limit reference points.

5 Results

In the current assessment, considerable effort was spent reviewing some of the underlying structural assumptions of the model to better understand the impact of these assumptions on the assessment results. This section briefly summarises the results of these preliminary analyses, principally the assumptions regarding regional structure and movement parameterisation. From these results, a preferred assessment was chosen as the “base case” assessment and the results of this model are presented in detail. Yield estimates and performance indicators are also derived for the base case assessment.

5.1 Area stratification and movement

Four different scenarios were considered regarding regional structure and movement.

- a) Four-region, fixed movement based on the movement schedule depicted in Figure 12 and no seasonal trend in catchability.
- b) Four-region, estimated movement, no seasonal trend in catchability.
- c) Four-region, estimated movement, seasonal trend in catchability.
- d) Single-region, seasonal trend in catchability.

The various options were assessed with respect to the estimated movement coefficients and seasonal catchability coefficients (Figure 14). The trends in adult biomass and annual recruitments were also compared (Figure 15).

For the two options estimating movement, large-scale northward movements were estimated for the 4th quarter and, to a lesser extent, in the first quarter, while smaller southward movements were estimated for the 2nd quarter (Figure 14). This is contrary to the assumed behavior of

albacore, whereby, a significant component of the stock moves southward during the summer and returns northward in autumn.

The four-region model with estimated movement and no seasonal catchability, yielded relatively low levels of adult biomass (Figure 15). This is likely to be due to the movement parameters that result in a high proportion of the adult stock being within the northern regions throughout the year and, therefore, vulnerable to the longline fisheries. The Taiwanese fisheries in the two northern regions have exhibited a steady decline in CPUE throughout the model period, while overall catches have been modest.

The contrary is the case for the four-region movement model with seasonal catchability estimated. While the estimated movement dynamics are comparable, this model exhibits seasonal trends in catchability that means the proportion of the exploitable biomass vulnerable to the longline fisheries in the northern regions is lower during certain times of the year, particularly the first and last quarters (Figure 14). This is the model's representation of the lower (higher) CPUE observed from the northern longline fisheries during the summer (winter). The model estimates higher catchability coefficients in the southern regions in the first two quarters to explain the observed increase in longline CPUE during that period. The introduction of the estimation of the seasonal catchability coefficients resulted in a large increase in the overall level of adult biomass for the stock (Figure 15).

The four-region model with fixed movement was an attempt to approximate the assumed movement dynamics of the stock. The fixed movement approximated the adult biomass trajectory derived from the single-region model. However, an examination of the model fit revealed persistent seasonal trends in the effort deviations for the main longline fisheries (Figure 16). For example, the low effort deviates for the two southern Taiwanese longline fisheries in the 1st and 4th quarters indicates that the observed albacore CPUE is higher than predicted from the model. This indicates that the assumed movement schedule is not adequately describing the movement dynamics of the population and/or there is a significant change in the seasonal catchability within the model that is not currently being taken into account (Figure 15).

Several alternative movement schedules were investigated to improve the performance of the four-region, fixed movement model; however, none of these attempts were a significant improvement on the model presented. The assumption of equivalent seasonal movements between regions 1 and 3 and regions 2 and 4 may not be appropriate. Further, given the differences in size selectivity between the northern and southern regions, it may be necessary to formulate age-specific movements.

In comparison to the four-region models, the single-region model can only explain seasonal differences in catch rate via the estimation of the seasonal catchability coefficients for each fishery. The seasonal trends in catchability from the single-region model were consistent with current assumptions regarding the availability of fish between the region-specific fisheries (Figure 14). Catchability was high in the northern regions during the 2nd and 3rd quarters and lower in the 1st and 4th quarters and highest in the southern regions in the 2nd quarter — broadly consistent with the assumed southern migration of albacore during the summer.

In conclusion, these results indicate that the four-region model is highly sensitive to either the imposed movement schedule (fixed movement) or the estimation of movement parameters and seasonal catchability coefficients. There is limited tagging data available to reliably estimate movement and estimates of movement are contrary to the assumed movement dynamics of the species. On this basis, it was decided not to proceed with the four region structure of the model.

Instead, a more parsimonious approach is to assume one single region and account for the effects of movement implicitly through maintaining the regional definitions of the individual fisheries and the estimation of seasonal catchability coefficients for each fishery.

5.2 Fit diagnostics (single-region model “base case”)

The performance of the model can be assessed by comparing the input data (observations) with the three predicted data classes – the total catch data, the length frequency data and the tagging data. In addition, the estimated effort deviations provide an indication of the consistency of the model with the effort data. The following observations are made concerning the various fit diagnostics:

- The log total catch residuals by fishery are shown in Figure 17. The residuals are all relatively small and, for most fisheries, generally show even distributions about zero. However, the notable exception is the trend in the residuals for the Taiwanese longline fisheries – the only fisheries where annual catchability is constant throughout the model period. These fisheries and, in particular the two northern fisheries (2 and 8) exhibit positive residuals (catch underestimated) at the start and end of the series and negative residuals during the middle of the series Figure 17 indicating a systematic lack of fit to the catch data for these fisheries.
- Overall, there is a good fit to the observed and predicted length data aggregated over time, particularly for the longline fisheries operating in the northern regions (fisheries 1–12) (Figure 18). These fisheries are characterized by a single length mode comprised of large, adult fish. There is also a good fit to the aggregated longline length data from the fisheries in region 4, although there is considerable deviation in the fits from the region 3 longline fisheries (fisheries 13–16) (Figure 18). Length samples from these fisheries were often dominated by strong modes of relatively small fish that were not predicted by the model indicating some inconsistency in the cohort strengths between the observed between the various fisheries. This is also evident from the poor fit to the second mode (2+ year age class) in the length data from the troll and drift net fisheries in region 3 (Figure 13). By comparison, there is a good fit to the length data from the same method fisheries operating in region 4.
- For each fishery, the observed and predicted proportion of “large” fish (greater than 90 cm for longline; 70 cm for other fisheries) in the catch was compared for each sample (quarter) (Figure 19). For a number of the main longline fisheries, there is a strong temporal trend in the residuals, in particular the three main Taiwanese longline fisheries (fisheries 2, 8 and 18) all reveal a positive trend in the residuals i.e. the model increasingly under-estimates the proportion of large fish observed in the catch in recent years (see Figure 9). There is also some temporal variability in the fit to the length data from the Japan/Korea longline fisheries in the southern regions (fisheries 13 and 17) (Figure 19).
- The model predicts the number of tag recoveries from the population at each time interval (Figure 20). This is a function of the cumulative number of tag releases in the preceding period, the loss of tags from the population (due to natural mortality and previous catches), the level of fishing effort, the fishery specific selectivity and catchability, and the fishery specific reporting rate for tag recoveries. Overall, relatively low numbers of tag returns are predicted at each time interval by the model consistent with the fishery observations (Figure 20). The model broadly fits the observed temporal trend in tag recoveries, increasing in the early 1990s following the release of the majority of the tags and then attenuating of the following decade as tags are lost from the population. However, the relatively high number of tag returns in 1994 is substantially underestimated by the model (Figure 20).
- The observed and predicted recoveries can also be compared with respect to the period at liberty of the tagged fish (Figure 21). The model predicts at returns decline steadily with

increased time at liberty, largely due to the cumulative effects of natural and fishing mortality. However, the model significantly underestimates the returns from the fishery for fish at liberty for 2–4 years (Figure 21). Based on the length at release, most of these recovered tags are likely to represent fish recruiting into the longline fishery (at about 5–7 years old).

- The tagging data is relatively uninformative in the model, largely due to the model's freedom to estimate fishery specific report rates of tag recoveries. For each fishery, reporting rates are assumed constant over time. This assumption may not be appropriate given the level of publicity associated with the initial release/recovery period. The reporting rates also implicitly account for other sources of tag loss from the population such as tag induced mortality following release and tag shedding. No independent data were available regarding the reporting rates from individual fisheries, although it was assumed that tag reporting rates were the same for all Taiwanese longline fisheries and, similarly, for all Japan/Korea longline fisheries.
- Overall, the highest estimated reporting rate was from the New Zealand longline fishery, while the Taiwanese longline fisheries all had a relatively high reporting rate (35%) reflecting the relatively high number of tags returned from these fisheries, while reporting rates for the Japan/Korea longline fisheries were low (Figure 22). The negligible reporting rates for many of the domestic longline fisheries may just be an artifact of the low level of fishery activity in these fisheries during the early 1990s and/or the lack of tagged fish in the older age classes harvested by these 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 23). If the model is coherent with the effort data, we would expect an even scatter of effort deviations about zero. 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. Such trends are evident in the effort deviations from the Taiwanese longline fisheries, particularly during the early period of the fishery. Initial catch rates from the fishery were very high and declined sharply during the subsequent 10 years, particularly in regions 2 and 4 (see Figure 7). Given the assumption of constant annual catchability for these fisheries, the model has accounted for these high initial catches by estimating strong positive effort deviations for the initial period of the fishery (Figure 23). The systematic decline in effort deviations during the 1960s and 1970s enabled the model to improve the fit the observed catches during the period of rapid decline in catch rates from the fisheries. Although, as noted above, the model is still under-estimating the catches in these fisheries in the balancing of the penalties associated with the effort deviates and the catch likelihood.
- These systematic trends in the effort deviations for the Taiwanese longline fisheries are symptomatic of inconsistencies in the model population dynamics and the observations from the fishery catch and effort data. This is further illustrated by comparing the estimated exploitable biomass for each fishery with the individual observations of catch and effort (scaled by catchability) from the fisheries (Figure 24). The model is unable to fit the high values of CPUE observed during the 1960s and early 1970s or the lower values of CPUE in the early 1980s. The figure also illustrates the high variation in the seasonally corrected CPUE data indicating the lack of precision associated with the catch and effort series - the principal index of stock abundance in the model.
- High negative effort deviates were also estimated for a number of fisheries, most notably the troll fishery in region 3 and the Japan/Korea longline fisheries in all regions, accounting for quarters with substantially lower catches than predicted from the level of effort (Figure 23).

For the troll fishery, the low effort deviations may represent a decline in the availability of the juvenile age classes to the fishery. Availability may be influenced by changes in oceanographic conditions, for example, the low effort deviations estimated in the model for the 1992–95 corresponded to a period of sustained El Niño conditions. For the Japan/Korea longline fisheries, the low effort deviations may correspond to changes in targeting practices by the two fleets, although examination of these effects would require a detailed analysis of the composite catch and effort data.

5.3 Model parameter estimates (single-region model “base case”)

5.3.1 Catchability

Annual catchability for the four Taiwanese longline area fisheries was held constant over the entire period of the model, although allowed to vary seasonally (Figure 25). For these fisheries, catchability was higher in the two northern areas (fisheries 2 and 8) compared to the southern area fisheries (fisheries 14 and 18).

Strong temporal trends in catchability are evident from other fisheries, most notably the strong decline in catchability of the Japan/Korea fishery during the 1960s (fisheries 1, 7, 12, and 16) (Figure 25). In most areas, catchability for these fisheries remained very low for the remainder of the model period, with the exception of the increase in catchability in region 3 (fishery 12). Many of the domestic longline fisheries reveal an initial increase in catchability during the development of the fishery and then a stabilization of catchability during the subsequent period. Exceptions to this trend were the declines in catchability evident in the Samoa/American Samoa and Tonga longline fisheries (Figure 25). In recent years, catchability has increased in the New Zealand troll fishery, while catchability has declined in the troll fishery operating in region 4.

For all fisheries, catchability was allowed to vary seasonally. In general, catchability of the longline fisheries was highest in the northern regions (1 and 2) during the second and third quarters and lower during the first and fourth quarters (Figure 25). For the southern regions (3 and 4) catchability was generally higher in the first and second quarters and lower in the third and fourth quarters. For the troll fisheries, catchability was highest during the first two quarters of the year (Figure 25).

5.3.2 Selectivity

The longline fisheries in the northern regions (fisheries 1–12) principally catch older, adult albacore, with very low selectivity for juvenile fish (5 years and younger), 50% selectivity occurring at about 8 years of age, and full selectivity approached at about 15 years (Figure 26). In contrast, younger fish are more vulnerable to the longline fisheries operating in the southern regions (fisheries 13–19) and juvenile fish represent a significant component of the catch from these fisheries (Figure 26). The troll and drift net fisheries principally exploit the 2–4 year age classes and the selectivity of the older age classes is very low.

5.3.3 Growth and natural mortality

The estimated growth curve is shown in Figure 27. Growth rates are estimated to be slightly higher during the first 7 years compared to the established growth parameters used as starting values in the model.

Natural mortality for age classes was estimated to be 0.343 (95% confidence interval 0.316–0.373), slightly lower than the initial value of 0.4.

5.4 Stock assessment results

5.4.1 Recruitment

There is considerable temporal variation in recruitment over the model period (Figure 28). Annual recruitment is estimated to have been low prior to 1960, high during the 1960s and early 1970s, higher in the late 1980s and early 1990s, and relatively low in the subsequent period. The recruitment estimates have broad confidence intervals indicating substantially model uncertainty, particularly during the early period (1960s and 1970s) (Figure 28).

The low initial recruitment is consistent with the small proportion of large fish observed in the longline fisheries during the 1960s and early 1970s, while the estimates of high recruitment in the during the 1960s and early 1970s is attributable to the observation of increased abundance of larger fish in the longline catch in the late 1970s and 1980s (see Figure 9). The high recruitment estimated during this period is also driven by the high initial CPUE observed from the Taiwanese fishery, while the decline in recruitment in the late 1970s/early 1980s allows the model to attempt to fit some of the large decline observed in CPUE from these fisheries during the 1970s and 1980s. Similarly, the increase in recruitment in the late 1980s/early 1990s is likely to be influenced by the increase in CPUE observed from the Taiwanese fisheries in the mid 1990s (see Figure 7).

5.4.2 Biomass

The annual trends in total and adult biomass are consistent with the temporal trend in recruitment described in the previous section. Biomass was estimated to be low during the 1950s, increasing during the 1960s in response to increased recruitment, high through the 1970s and early 1980s, and then subsequently declining (Figure 29). There is a high level of uncertainty associated with the annual biomass estimates, particularly for the 1970s and early 1980s.

5.4.3 Fishing mortality

Overall, fishing mortality (exploitation) rates for adult and, particularly, juvenile albacore are estimated to have remained low throughout the history of the fishery (Figure 30). For adult fish, exploitation rates increased during the initial development of the fisheries, but declined in the late 1960s and 1970s due to the increased level of adult biomass (following high recruitment). Exploitation rates remained relatively constant through the 1970s and 1980s then subsequently increased over the last five years (Figure 30) in response to higher catches (see Figure 4) and lower levels of adult biomass.

The fishing mortality rates for juvenile albacore peaked, albeit at a very low level, in 1989–90 corresponding to the peak period of drift net fishing (Figure 30). There has been a gradual increase in exploitation rates during the last decade mainly attributable to increased catches from the New Zealand troll fishery.

5.4.4 Fishery impact

An indicator of the impact of fishing on the stock is to compare the biomass trajectories with fishing and the predicted biomass trajectory in the absence of fishing (assuming fishing has no impact on the annual recruitment). The impact can be expressed as a proportional reduction in biomass ($1 - B_t/B_{0t}$) and calculated for different components of the stock; juvenile, adult, and the proportion of the stock vulnerable to the main longline fisheries.

For juvenile and adult albacore, the fishery impacts are consistent with the estimated fishing mortality rates. The fishery impact on adult fish has increased over the last decade and is estimated to be currently (2003) about 15% i.e., adult biomass has been reduced by 15% due to the impact of fishing (Figure 31). The current level of impact on the juvenile component of the stock is negligible (about 1%).

The level of impact on the component of the stock vulnerable to the longline fisheries (longline exploitable biomass) is considerably higher than for adult fish, increasing from about 15% in the 1980s to about 30% in recent years (Figure 31). This is due to the increased catch from the longline fisheries in recent years and the age-specific selectivity of the longline fisheries that harvest fish in the oldest age classes (Figure 32). The longline fishery is only harvesting a small component of the stock so any increase in catch is likely to result in a substantial increase in the impact on the longline exploitable biomass (Figure 33).

The relatively high impact on the longline exploitable biomass is particularly evident in the longline fisheries operating in the northern regions (fisheries 1–12), while the impact on longline exploitable biomass in the southern regions is lower due to a higher proportion of younger fish in the catch (Figure 34). The impact of the fishery on the exploitable biomass in the troll and drift net fisheries has been negligible throughout the history of the fishery (Figure 34).

5.4.5 Yield analysis

Symbols used in the following discussion are defined in Table 5. The yield analyses conducted in this assessment incorporate the SRR (Figure 35) into the equilibrium biomass and yield computations. The estimated steepness coefficient of the SRR is 0.88, close to the prior mode of 0.90 (Figure 36). Equilibrium yield and total biomass as functions of multiples of the 2000–2002 average fishing mortality-at-age (*fmult*) are shown in Figure 37. Yield is maximized at *fmult* = 19 for a *MSY* of 183,000 t per annum. This implies that the ratio $F_{current}/\tilde{F}_{MSY}$ is approximately 0.05. The equilibrium biomass at *MSY* is estimated at 1,056,000 t, approximately 44% of the equilibrium unexploited biomass.

5.4.6 Stock assessment conclusions

A number of quantities of potential management interest associated with the yield analyses are provided in Table 6. In the top half of the table, absolute quantities are provided, while the bottom half of the table contains ratios of various biomass and fishing mortality measures that might be useful for stock monitoring purposes. It is useful to distinguish three different types of ratio: (i) ratios comparing a measure for a particular time period with the corresponding equilibrium measure; (ii) ratios comparing two equilibrium measures (rows shaded grey); and (iii) ratios comparing two measures pertaining to the same time period (row shaded black). Several commonly used reference points, such as $B_{current}/\tilde{B}_{MSY}$ and $F_{current}/\tilde{F}_{MSY}$ fall into the first category. These ratios are usually subject to greater variability than the second category of ratios because recruitment variability is present in the numerator but not in the denominator. Indeed, the range of values observed over the four analyses conducted in this assessment suggests that the category (ii) ratios are considerably more robust than those in category (i).

The ratio $B_{current}/B_{current,F=0}$ provides a time-series index of population depletion by the fisheries. Levels of depletion of total biomass have been low throughout the model period, although depletion levels have increased to about 0.91 (i.e., total biomass reduced by 10% due to

the impact of fishing). This represents a low level of stock-wide depletion that would be well above the equivalent equilibrium-based limit reference point ($\tilde{B}_{MSY}/\tilde{B}_0 = 0.44$).

The other reference points that are useful in indicating the current status of the stock are $\tilde{Y}_{F_{current}}/MSY$ (0.29), $\tilde{B}_{F_{current}}/\tilde{B}_{MSY}$ (2.25) and $S\tilde{B}_{F_{current}}/S\tilde{B}_{MSY}$ (5.16). The yield-based reference point $\tilde{Y}_{F_{current}}/MSY$ indicates that there is considerable potential to expand long-term yields from the fishery at the current pattern of age-specific selectivity. Both biomass-based reference points indicate that the long-term average biomass should remain well above that capable of producing *MSY*.

The ratios of $F_{current}/\tilde{F}_{MSY}$ and $S\tilde{B}_{F_{current}}/S\tilde{B}_{MSY}$ reveal that overfishing of south Pacific albacore is not occurring, nor is the stock in an overfished state (Figure 38 and Figure 39).

6 Discussion and conclusions

The current stock assessment represents a considerable reappraisal of the underlying model structure used in the previous assessments of south Pacific albacore (Hampton 2002, Labelle & Hampton 2003). The main factors considered in the new assessment were as follows.

- The appropriate stratification of the model spatially and by fishery. This resulted in the inclusion of additional domestic longline fisheries and may allow the results of the assessment to be applied to investigate management issues at a scale approximating the Exclusive Economic Zones of Pacific Island countries and territories.
- An investigation of the performance of the model to the assumptions of seasonal movement between model regions. Based on this analysis, it was decided that there was insufficient data for the model to independently estimate the movement dynamics of the stock and the spatial structure was abandoned in favour of a single region model that maintained the region definitions of the individual fisheries.
- There was no attempt to estimate age specific natural mortality, as undertaken in previous assessments. It was decided that there were insufficient tagging data to estimate these parameters and the estimation is likely to be confounded with other parameters, such as tag reporting rates and selectivity.
- A number of other sensitivity analyses were undertaken to explore the impact of assumptions about the number of age classes included in the model (12 vs. 20) and the method of estimation of the selectivity functions for the longline fishery. These results were not presented although the assumptions were found to have only a small impact on the main performance indicators for the assessment. However, the model was highly sensitive to the relative weighting of the effort data from the Taiwanese longline fisheries.
- The sensitivity of the model to assumptions regarding initial conditions was examined by comparing models commencing in 1952 and 1960. The former model assumed unexploited equilibrium conditions while the later included an estimate of the impact of fishing mortality on the initial conditions to account for catches taken in the preceding years. The model commencing in 1960 estimated very high initial impacts on the stock (particularly on longline exploitable biomass), largely due to the observation of few large fish in the catch during the earlier years. However, the magnitude of the fishery impact appeared to be inconsistent with the level of catch that had been taken in the preceding period. On this basis, only the results from the model commencing in 1952 were reported.

The range of analyses undertaken and the sensitivity of the results to a number of the structural assumptions of the model highlight the uncertainty of the current assessment. This is also evident in the examination of the range of model diagnostics that indicate significant inconsistencies between the observed trends in catch rate from the Taiwanese longline fisheries and the length frequency data from the longline fishery. In particular, the model is not able to fit the rapid decline in catch rate observed from the fishery in the earlier years or the increased numbers of large fish observed in the longline catch from the Taiwanese fleet in recent years.

Overall, there appears to be a conflict between the two data sources and the model attempts to mediate these observations via the time-series of recruitment, in particularly low recruitment during the early period of the fishery followed by a period of high recruitment in the 1960s and 1970s. Consequently, there is a very high level of uncertainty regarding the historical trends in stock abundance (as represented by the confidence intervals of the biomass trajectory). Future improvements to the assessment should concentrate on a detailed reanalysis of the two main data sets.

The utility of the catch and effort data from the Taiwanese longline fishery as the principal index of stock abundance should be explored in more detail. The current analysis includes these as a nominal index as previous attempts to standardize these data for spatial and temporal changes in fishing activity have not revealed any significant difference from the nominal series (Langley 2003). Nevertheless, these data warrant further analysis, particularly to explain the large decline in CPUE during the period following the development of the fishery and to account for the effects of recent shift towards targeting of bigeye tuna within region 2. There is also scope for a detailed analysis of the catch and effort data from the southern troll fisheries as these fisheries represent the only indicator of year class strength prior to recruitment into the longline fishery. This work is currently being undertaken under contract to the New Zealand Ministry of Fisheries.

The observed temporal trend in the length composition from the main longline fisheries, particularly during the early period of the fishery, is not consistent with the expected trend in length composition from a developing fishery; specifically, the increase in the proportion of large fish in the catch from the 1960s to the 1980s. As previously mentioned, the model explains this observation by high recruitment in the 1960s and 1970s, although these observations are not entirely consistent with the low CPUE from the early catch and effort data from the troll fishery around New Zealand. An alternative hypothesis not explored in the assessment model is that the increased length of fish caught by the longline fisheries was attributable to a shift in the selectivity of the longline fisheries. This may have occurred due to a change in longline gear configuration (e.g., deeper setting of longline gear may catch larger albacore) and/or changes in the spatial distribution of the operation of the longline fleet. These factors should be further examined, particularly as the length of albacore caught by the Taiwanese fleet has continued to increase in recent years.

These observations also strengthen the need to maintain the current sampling of the troll fishery around New Zealand (e.g. Griggs 2004) and in the STCZ. The length composition from these fisheries provides the only source of information concerning the relative strength of the juvenile year classes prior to their recruitment to the longline fisheries.

Limited tagging data were available for inclusion into the current assessment (a total of 138 recoveries). Future, large-scale tagging of albacore, using both conventional and electronic tags, would provide increased information concerning movement, growth, overall stock size, and exploitation rates. Small-scale albacore tagging programmes have been undertaken around the Samoa archipelago in recent years. However, the implementation of a larger-scale programme,

particularly targeting adult albacore, would require considerable development of current tagging techniques for the species.

The previous assessment by Hampton (2002) recognized that there was a high level of uncertainty with respect to stock size and explored this uncertainty via a sensitivity analysis (based on the assumed maximum tag-reporting rate). This analysis yielded broadly comparable levels of total biomass to the current assessment for a maximum tag reporting rate equivalent to the reporting rates estimated in the current assessment (about 35% for the Taiwanese longline fisheries).

Labelle & Hampton (2003) do not present estimates of absolute biomass for the stock, preferring instead to present trends in relative biomass. There are clear differences in the biomass trajectories between the 2003 assessment and the current assessment and recent fishery impacts on total biomass were estimated to be higher in the current study (10% compared to 3%). The previous study also estimated a much higher MSY for the fishery (in excess of 300,000 mt).

Based on the comparisons between these three assessments, there remains considerable uncertainty regarding the overall level of stock size. Therefore, it is important to qualify the results of the current and past assessments with other observations from the fishery. Some of these external observations are not independent of the model results as the data are already integrated in the assessment and, therefore, can be explained internally by the model. However, it is also important to consider alternative explanations for the same observations that might provide additional insight into the dynamics of the fishery. Specifically:

- Most of the longline albacore catch is taken in a relatively narrow latitudinal band (10–40° S). Overall catch rates for albacore in the subequatorial area are relatively low and areas of high catch rates appear to be localised (e.g. the early period of development of the Samoa fishery) or limited to discrete seasonal periods associated with the northern/southern movements of fish during winter/summer. These peaks in seasonal catch rate tend to persist for a couple of months and extend over a 10° latitudinal range (see Figure 3). On this basis, it would appear that the main component of the longline exploitable biomass resides in a relatively small area, suggesting a modest stock size.
- The observation of declines in catch rate from significant domestic longline fisheries (e.g. Fiji, Samoa, and French Polynesia) following periods of relatively high albacore catch (3,000–10,000 mt per annum) is indicative of local scale depletion of the stock (Langley 2004). This suggests a relatively low level of exploitable biomass is accessible to these fisheries and diffusion rates into the EEZ are lower than the peak levels of catch.
- It is also interesting to contrast the south Pacific albacore fishery with the albacore fishery in the north Pacific Ocean. The two fisheries are considered to be supported by separate biological stocks. However, both fisheries occupy a similar geographic range, albeit in the reciprocal hemispheres and support longline and surface fisheries. Annual catches from the north Pacific albacore fishery have fluctuated about 90,000 mt since the 1950s, with approximately half the catch taken by the longline fishery in recent years (Crone & Conser 2002). Recent total stock biomass is estimated to be about 500,000 mt, recent fishing mortality rates on the adult component of the stock were high (about 0.5), and recent catches (about 90,000 mt) were at about the MSY level.

These auxiliary observations tend to lend support to the hypothesis that the south Pacific albacore stock is capable of supporting a modest (80–150,000 mt per annum) fishery, rather than a substantially larger fishery. However, there remains a high level of uncertainty regarding the magnitude of the stock size.

The current assessment indicates that the current levels of exploitation of the total biomass are low ($B_{current}/B_{current,F=0} = 0.91$ and $F_{current}/\tilde{F}_{MSY} = 0.05$). Nevertheless, the current level of longline catch is estimated to be having a measurable impact on the portion of the stock vulnerable to the longline fishery. The magnitude of this impact is uncertain, although the “base case” assessment indicates that the current level of impact is about 30% and has increased sharply in recent years, although, the impact on the adult component of the stock is considerably less due to the age-specific exploitation pattern of the longline fisheries.

The model also indicates that substantial increases in yield could be taken from the fishery (current yields 55,000 mt; MSY 180,000 mt). However, higher yields would require higher levels of fishing effort resulting in lower levels of adult biomass and, due to the current exploitation pattern of the fishery, a much greater decline in the level of longline exploitable biomass. For example, the current model predicts that a five-fold increase in fishing effort would yield a three-fold increase in catch while the longline exploitable biomass would be reduced by 50%. The reduction in longline biomass would be expected to result in a similar decline in catch rates from the longline fishery. Thus, any consideration of management objectives and performance indicators for the south Pacific albacore fishery needs to also include an assessment of the economics of the operation of those longline fisheries targeting albacore in the region.

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Table 3: Main structural assumptions used in the albacore tuna one-region and four-region 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 poisson probability distribution.
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 ≤ 0.9 . All reporting rates constant over time.
Tag mixing	Tags assumed to be randomly mixed at the model region level after the first year following release.
Recruitment	Occurs as discrete events in June of each year. Recruitment is weakly related to spawning biomass with a 1 year lag via a Beverton-Holt SRR (beta prior for steepness with mode at 0.9 and SD of 0.1). Recruitment occurs in the southern regions only (four-region model).
Initial population	Equilibrium age structure in the region as a function of the estimated natural mortality.
Age and growth	20 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. 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, except Taiwanese longline, 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. Taiwan fisheries share common catchability in the four-region model only.
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	Constant with respect to age; uninformative prior distribution with mean 0.4 (no penalty).
Movement	Not relevant for the single region model. Fixed or estimated for the four region model as described in the text.

Table 4: Details of objective function components for the one region model.

Objective function component	
Number of parameters	2,497
Total catch log-likelihood	103
Length frequency log-likelihood	-281,888
Tag log-likelihood	574
Penalties	3,177
Total function value	-278,034
Maximum gradient at termination	0.0017

Table 5. Description of symbols used in the yield analysis.

Symbol	Description
$F_{current}$	Average fishing mortality-at-age for 2000–2002
F_{MSY}	Fishing mortality-at-age producing the maximum sustainable yield (<i>MSY</i>)
$\tilde{Y}_{F_{current}}$	Equilibrium yield at $F_{current}$
$\tilde{Y}_{F_{MSY}}$ (or <i>MSY</i>)	Equilibrium yield at F_{MSY} , or maximum sustainable yield
\tilde{B}_0	Equilibrium unexploited total biomass
$\tilde{B}_{F_{current}}$	Equilibrium total biomass at $F_{current}$
\tilde{B}_{MSY}	Equilibrium total biomass at <i>MSY</i>
\tilde{SB}_0	Equilibrium unexploited adult biomass
$\tilde{SB}_{F_{current}}$	Equilibrium adult biomass at $F_{current}$
\tilde{SB}_{MSY}	Equilibrium adult biomass at <i>MSY</i>
$B_{current}$	Average current (2000–2002) total biomass
$SB_{current}$	Average current (2000–2002) adult biomass
$B_{current, F=0}$	Average current (2000–2002) total biomass in the absence of fishing.

Table 6. Estimates of management quantities for the one region model. The highlighted rows are ratios of comparable quantities at the same point in time (black shading) and ratios of comparable equilibrium quantities (grey shading).

Management quantity	Units	
$\tilde{Y}_{F_{current}}$	t per year	53,000
$\tilde{Y}_{F_{MSY}}$ (or <i>MSY</i>)	t per year	183,000
\tilde{B}_0	t	2,406,000
$\tilde{B}_{F_{current}}$	t	2,377,000
\tilde{B}_{MSY}	t	1,056,000
$S\tilde{B}_0$	t	1,217,000
$S\tilde{B}_{F_{current}}$	t	1,191,000
$S\tilde{B}_{MSY}$	t	231,000
$B_{current}$	t	1,788,000
$SB_{current}$	t	989,000
$B_{current, F=0}$	t	1,958,000
$B_{current} / \tilde{B}_0$		0.74
$B_{current} / \tilde{B}_{F_{current}}$		0.75
$B_{current} / \tilde{B}_{MSY}$		1.69
$B_{current} / B_{current, F=0}$		0.91
$SB_{current} / S\tilde{B}_0$		0.81
$SB_{current} / S\tilde{B}_{F_{current}}$		0.83
$SB_{current} / S\tilde{B}_{MSY}$		4.29
$\tilde{B}_{F_{current}} / \tilde{B}_0$		0.99
$S\tilde{B}_{F_{current}} / S\tilde{B}_0$		0.98
$\tilde{B}_{MSY} / \tilde{B}_0$		0.44
$S\tilde{B}_{MSY} / S\tilde{B}_0$		0.19
F_{MSY}		0.17
$F_{current} / \tilde{F}_{MSY}$		0.05
$\tilde{B}_{F_{current}} / \tilde{B}_{MSY}$		2.25
$S\tilde{B}_{F_{current}} / S\tilde{B}_{MSY}$		5.16
$\tilde{Y}_{F_{current}} / MSY$		0.29

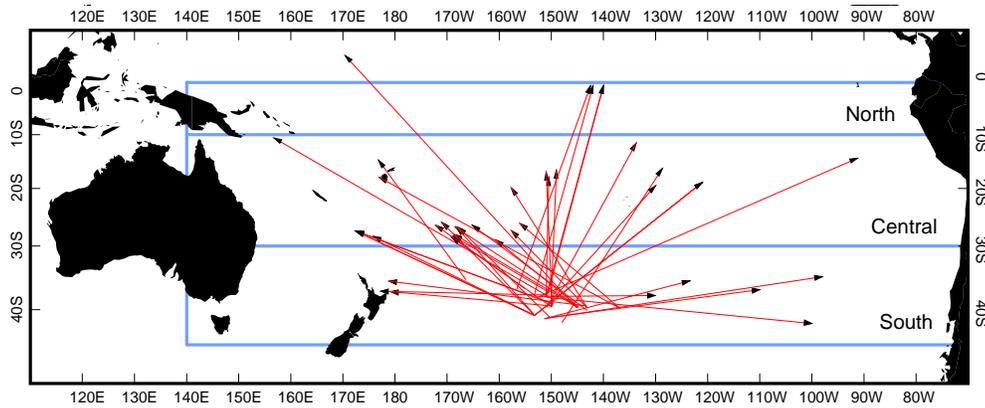


Figure 1. Movements of tagged South Pacific albacore (from Labelle & Hampton 2003).

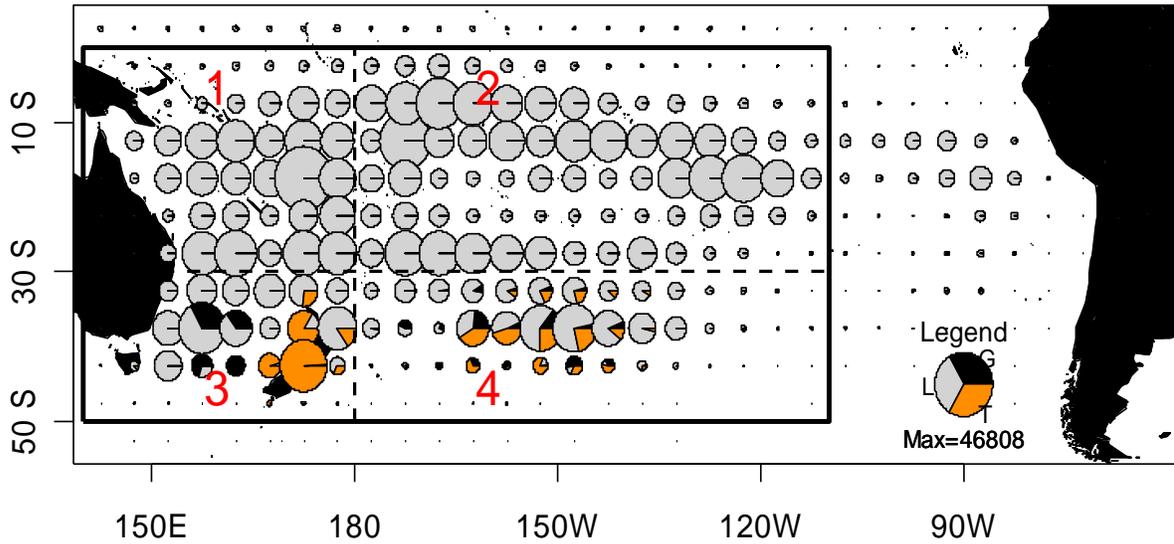


Figure 2: Total catch from 1960 to 2003 by 5 degree squares of latitude and longitude by fishing gear; longline (L), driftnet (G), and troll (T). The area of the pie chart is proportional to the total catch. The boundary of the stock assessment area is delineated by the black line and regional boundaries are delineated by the grey lines.

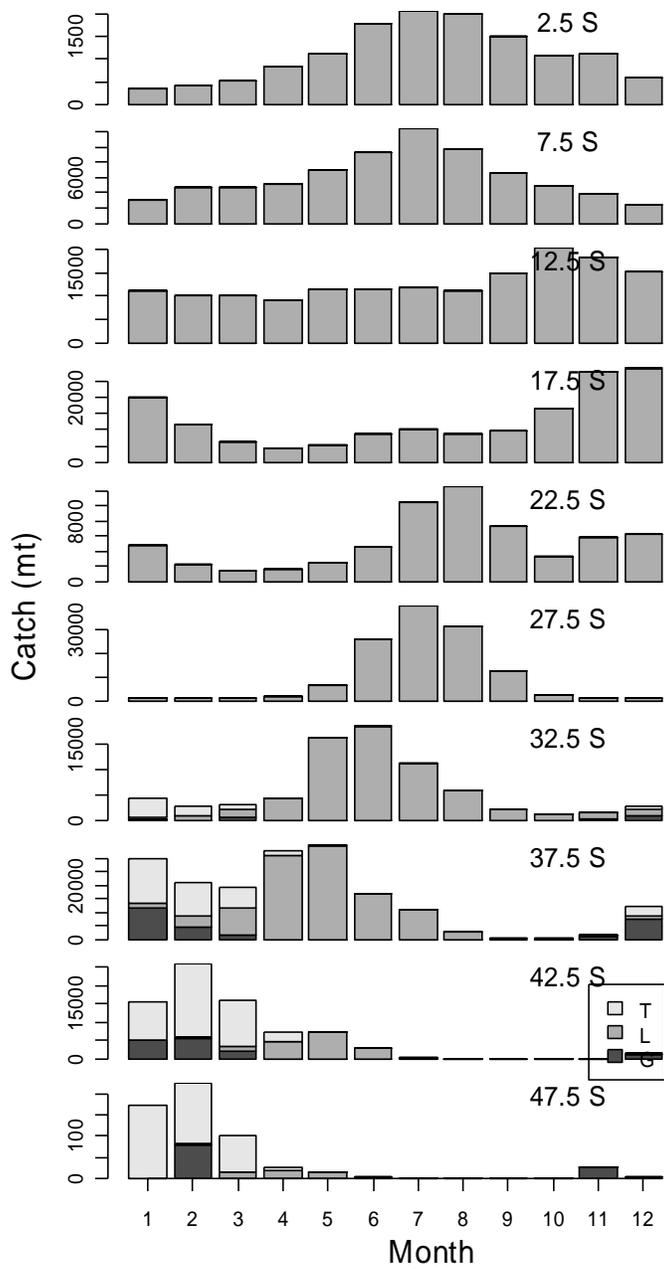


Figure 3: Cumulative monthly distribution of south Pacific albacore catch by gear (T, troll; L, longline; G, drift net) by 5 degree latitudinal band for 1980 to 2003 combined.

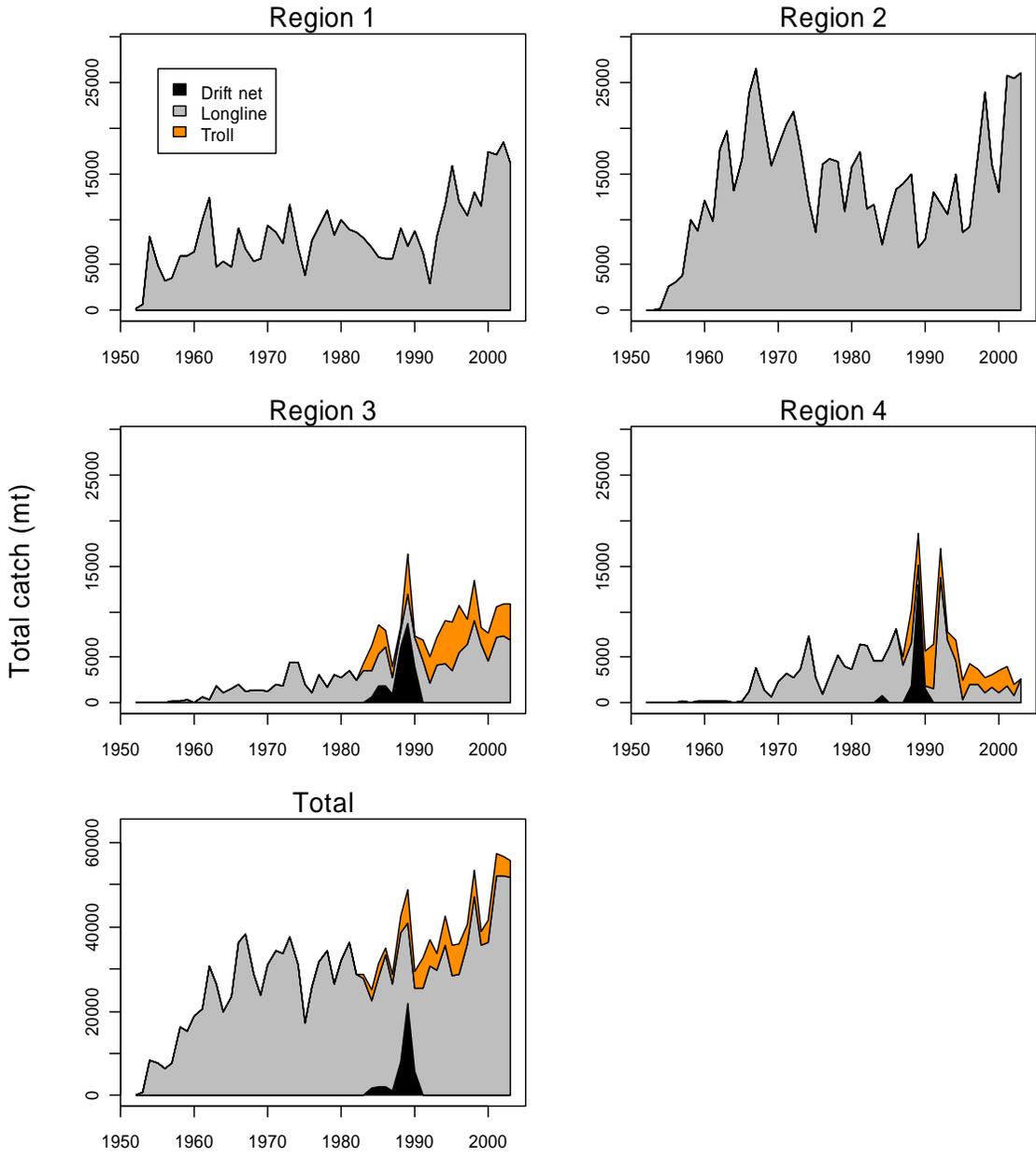


Figure 4: Annual catch (mt) of south Pacific albacore by fishing method and region and total combined annual catch for 1952 to 2003.

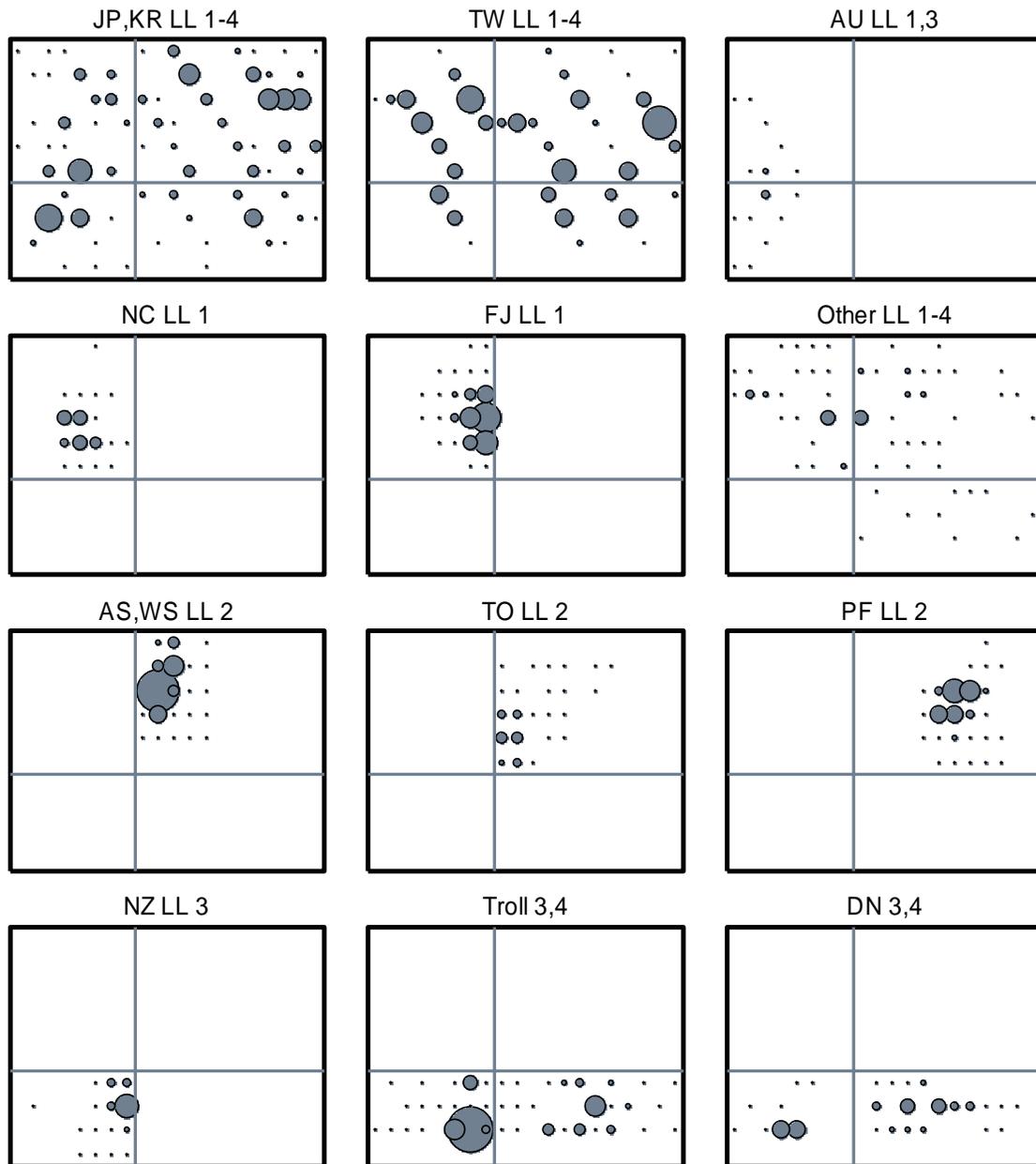


Figure 5: Cumulative albacore catch by fishery by 5 degree square of latitude and longitude from 1970–2002. The circle size is proportional to the cumulative catch (maximum circle size corresponds to 33,200 mt). The grey lines represent the region boundaries.

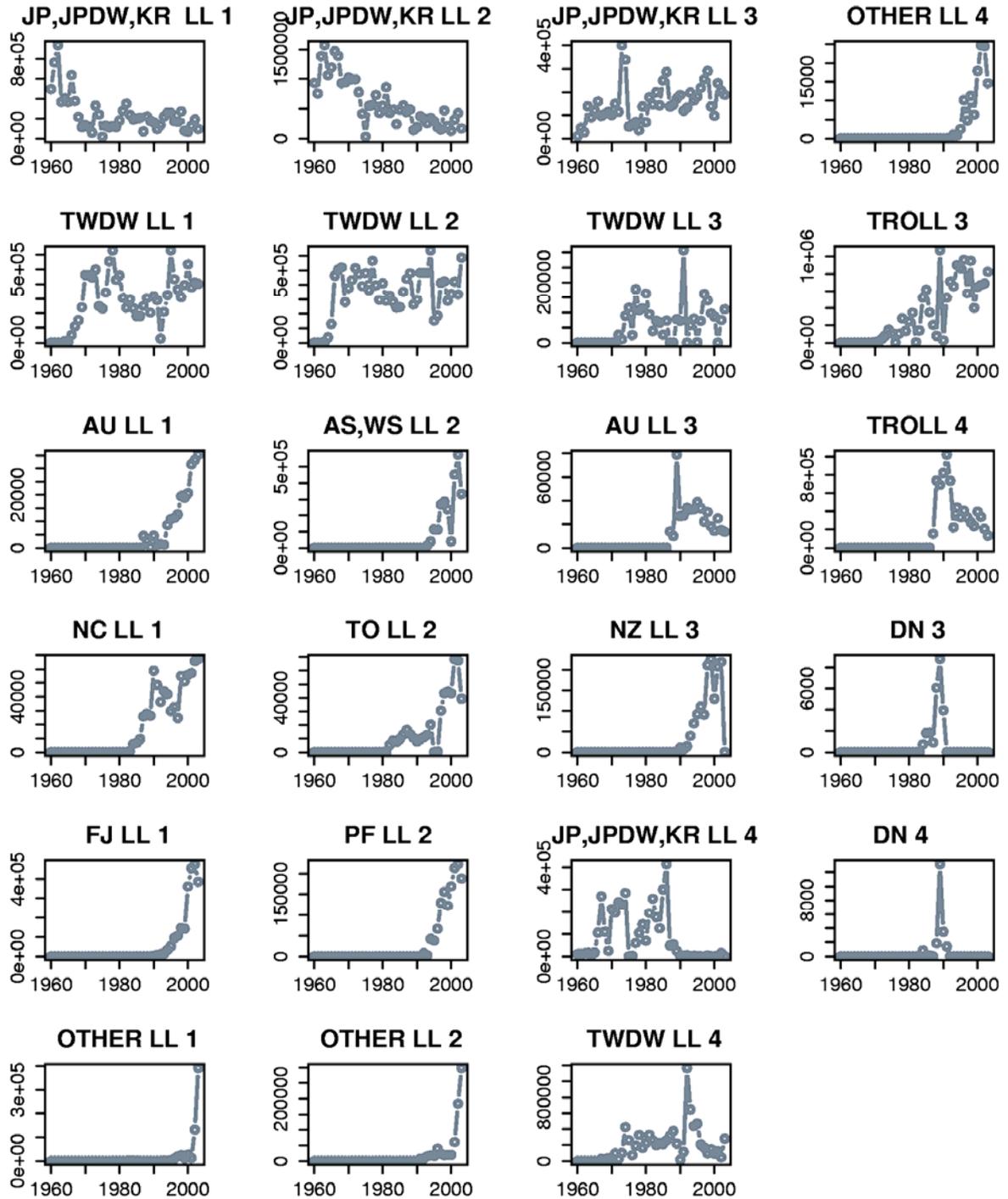


Figure 6: Annual catches by fishery (catches in numbers of fish for all fisheries except driftnet).

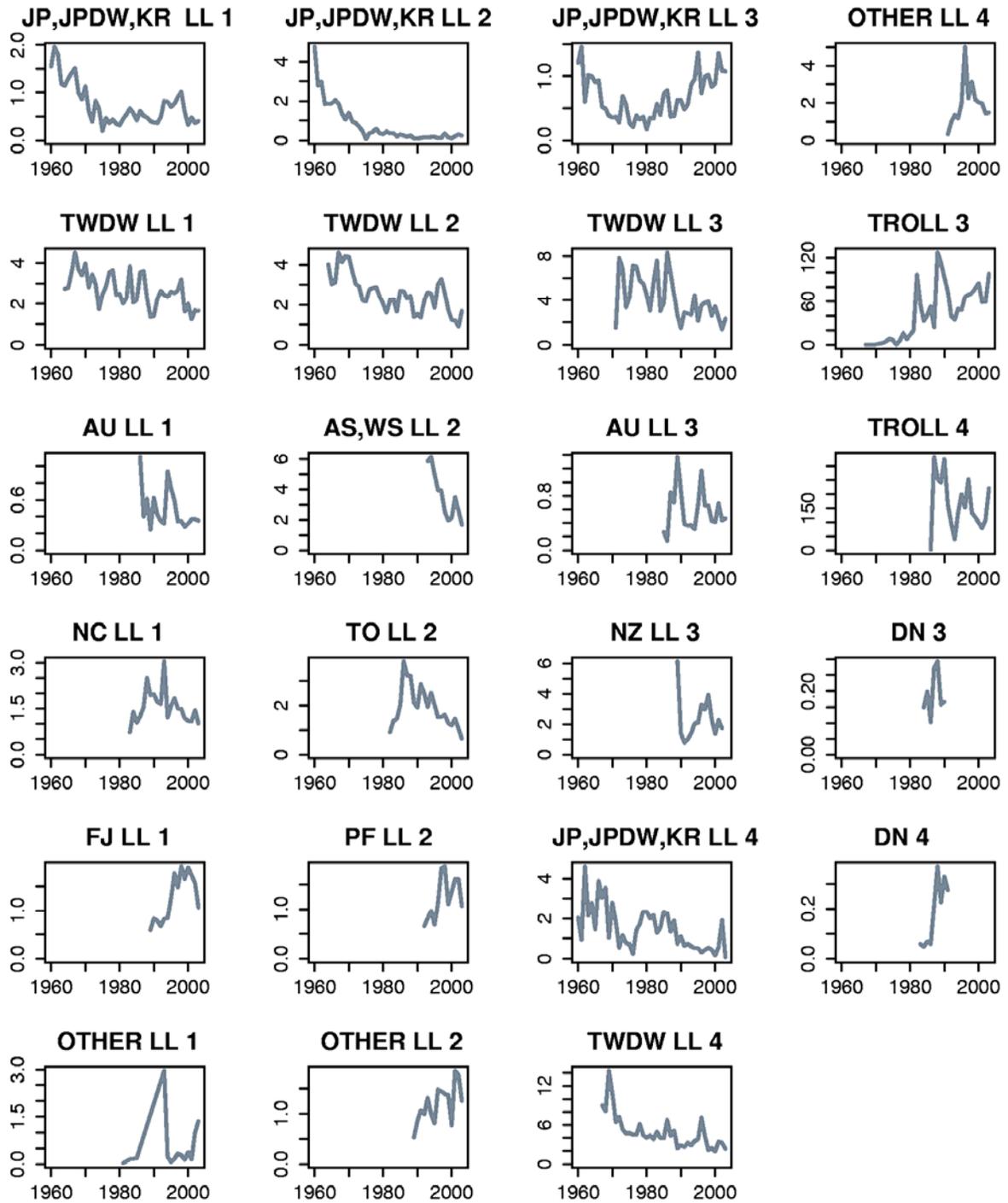


Figure 7: Annual average catch rates by fishery (longline catch rates expressed as number per 100 hooks; troll, number per vessel day fished; drift net, mt per day).

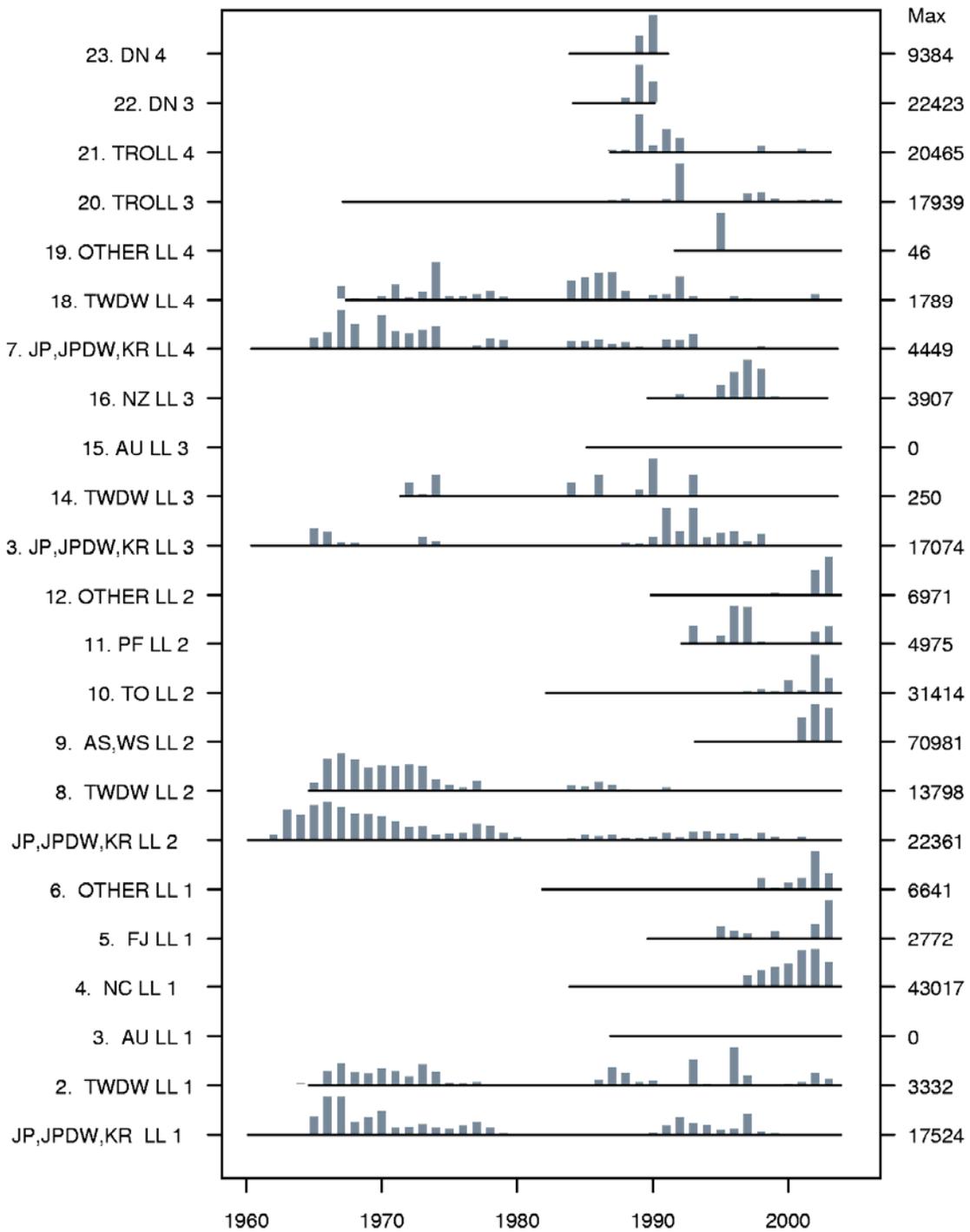


Figure 8: Length frequency samples by fishery and year. The number on the y-axis represents the maximum number of fish measured in a single year for the fishery. The frequency histograms are scaled relative to the maximum value for the fishery. The length of the x-axis denotes the period of catch and effort data from the fishery. No size frequency data were available before 1960.

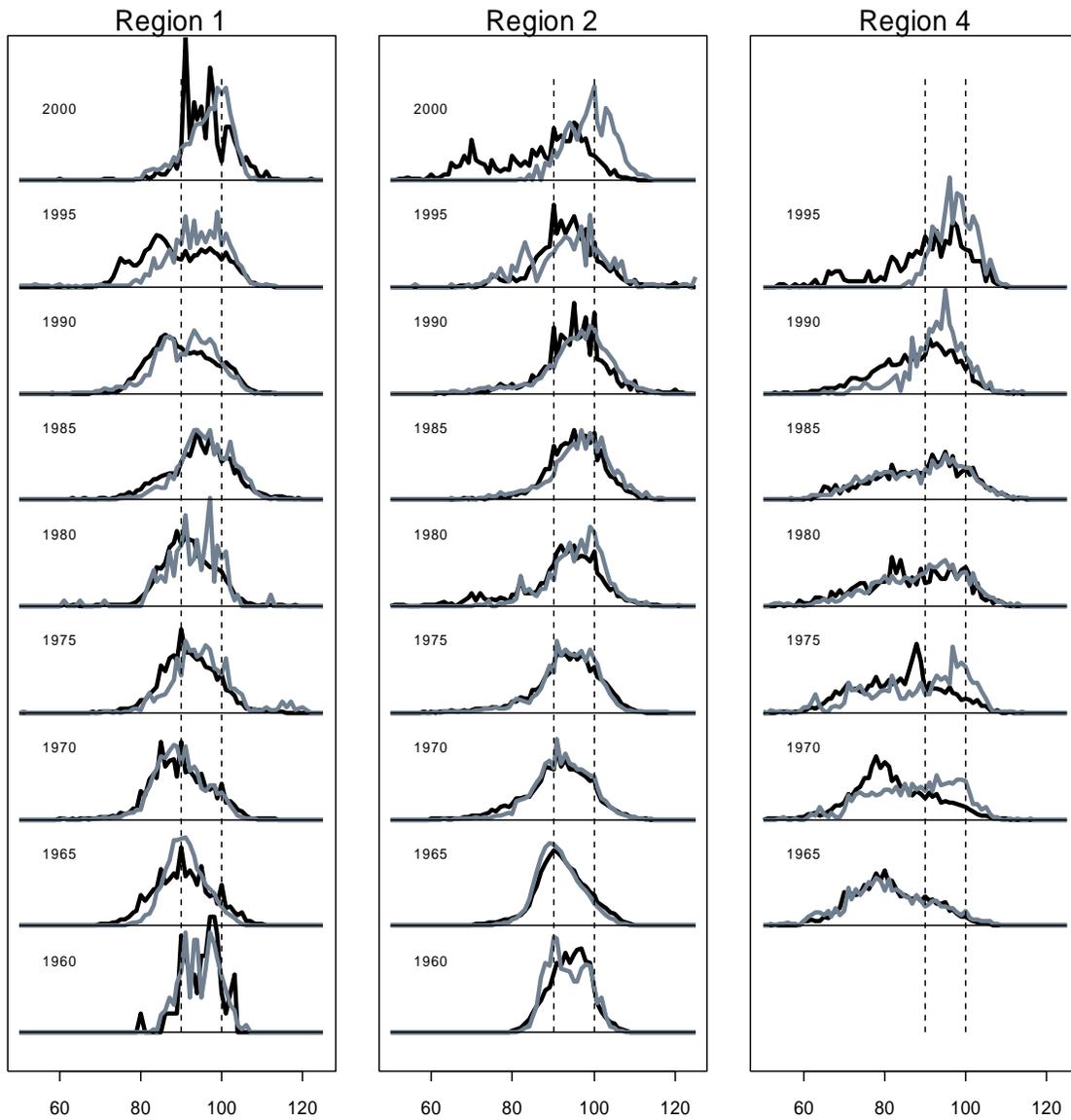


Figure 9: Five yearly aggregated length frequency distributions (fork length) of albacore from the Japan/Korea (black) and Taiwanese (grey) longline in regions 1, 2, and 4 (insufficient data were available from region 3). The year denotes the first year of the five-year period. The two dashed vertical lines are at 90 and 100 cm.

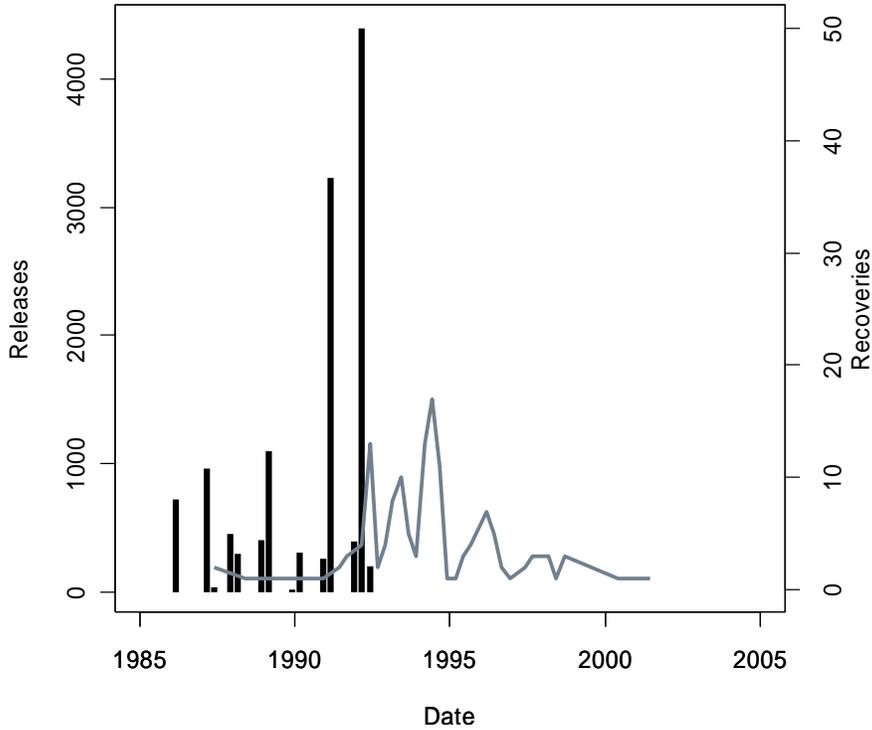


Figure 10: Tag releases (bars) and recoveries (line) by quarter for the south Pacific albacore fishery.

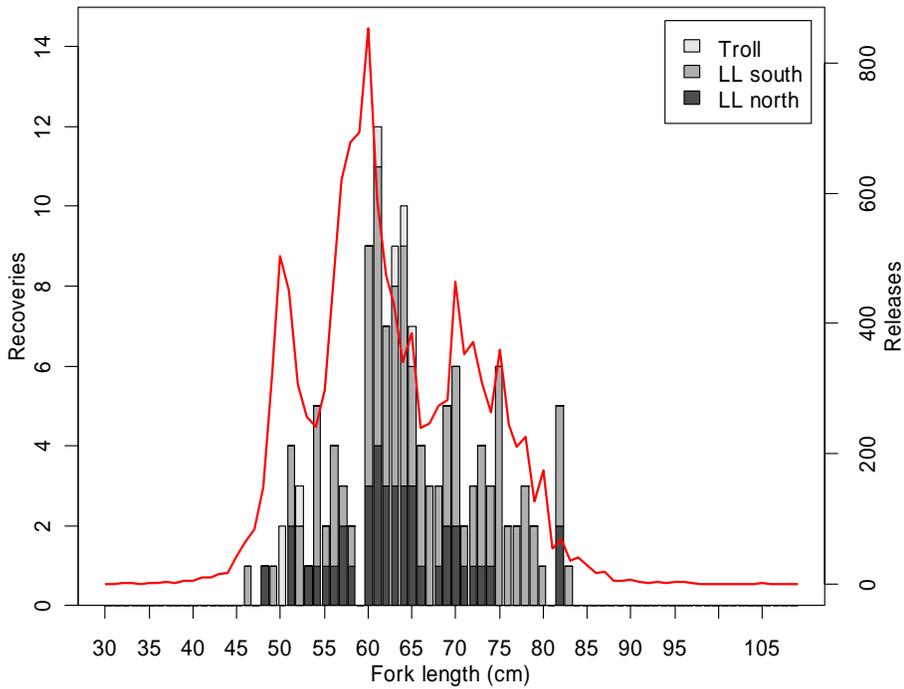


Figure 11: The total number of released tagged albacore (red line) and the number of recoveries (bar plot) by length class. The recoveries are aggregated by groups of fisheries; northern and southern longline fisheries and the troll fisheries.

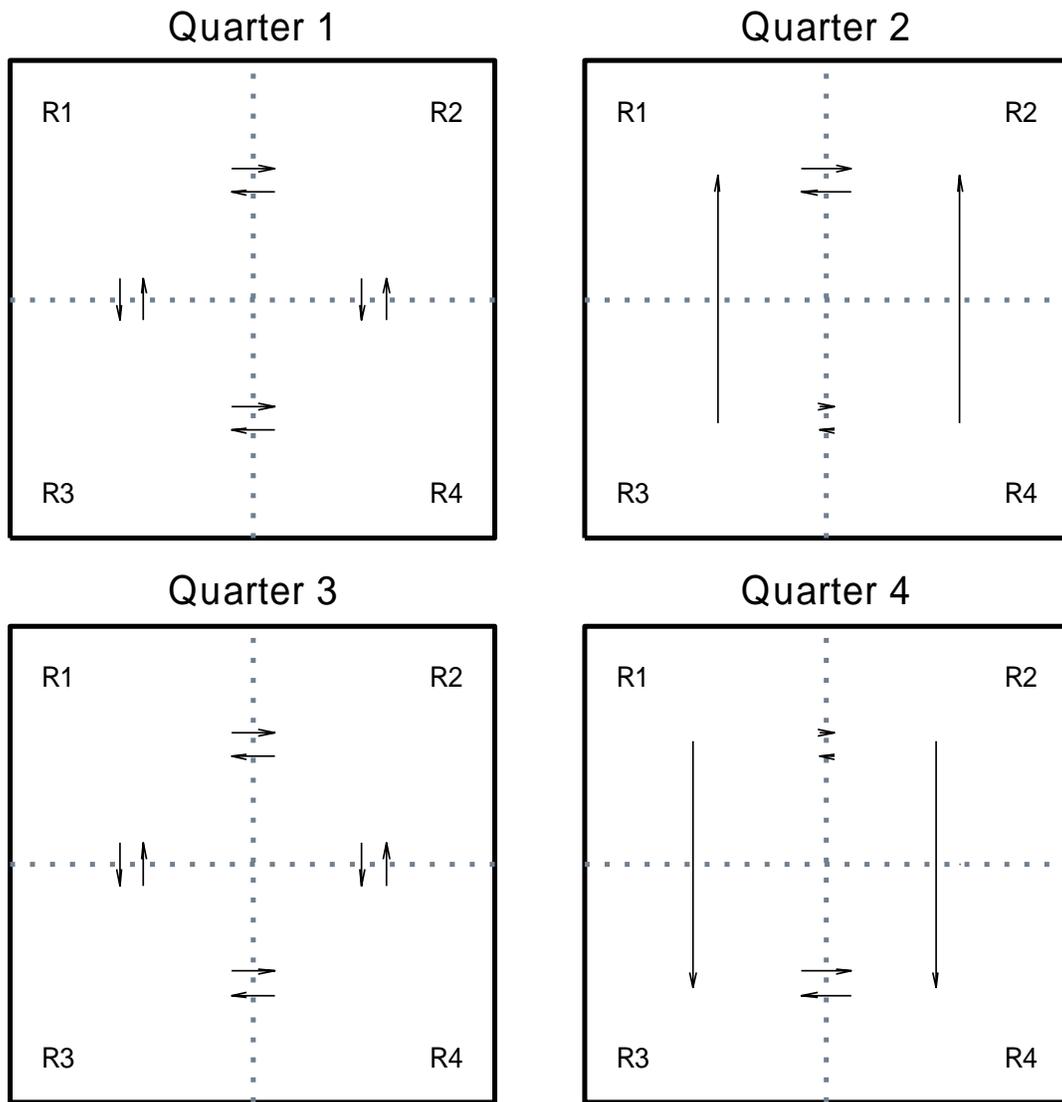


Figure 12: The quarterly movement schedule between regions used in the fixed movement model for the four region assessment. The length of the arrows is proportional to the magnitude of the movement.

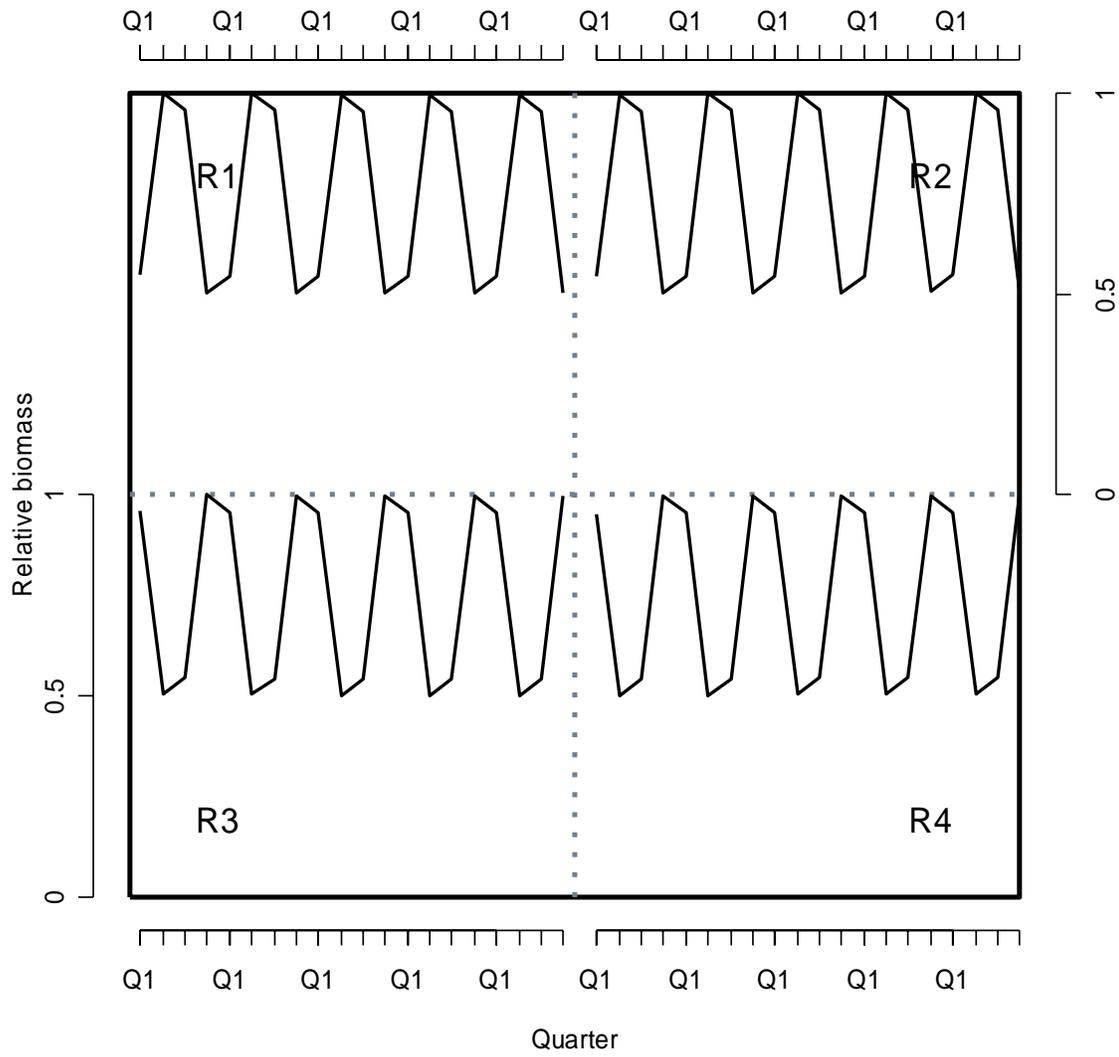


Figure 13: The fluctuations in relative biomass within a region by quarter for a theoretical population based on the fixed movement schedule used in the four region model.

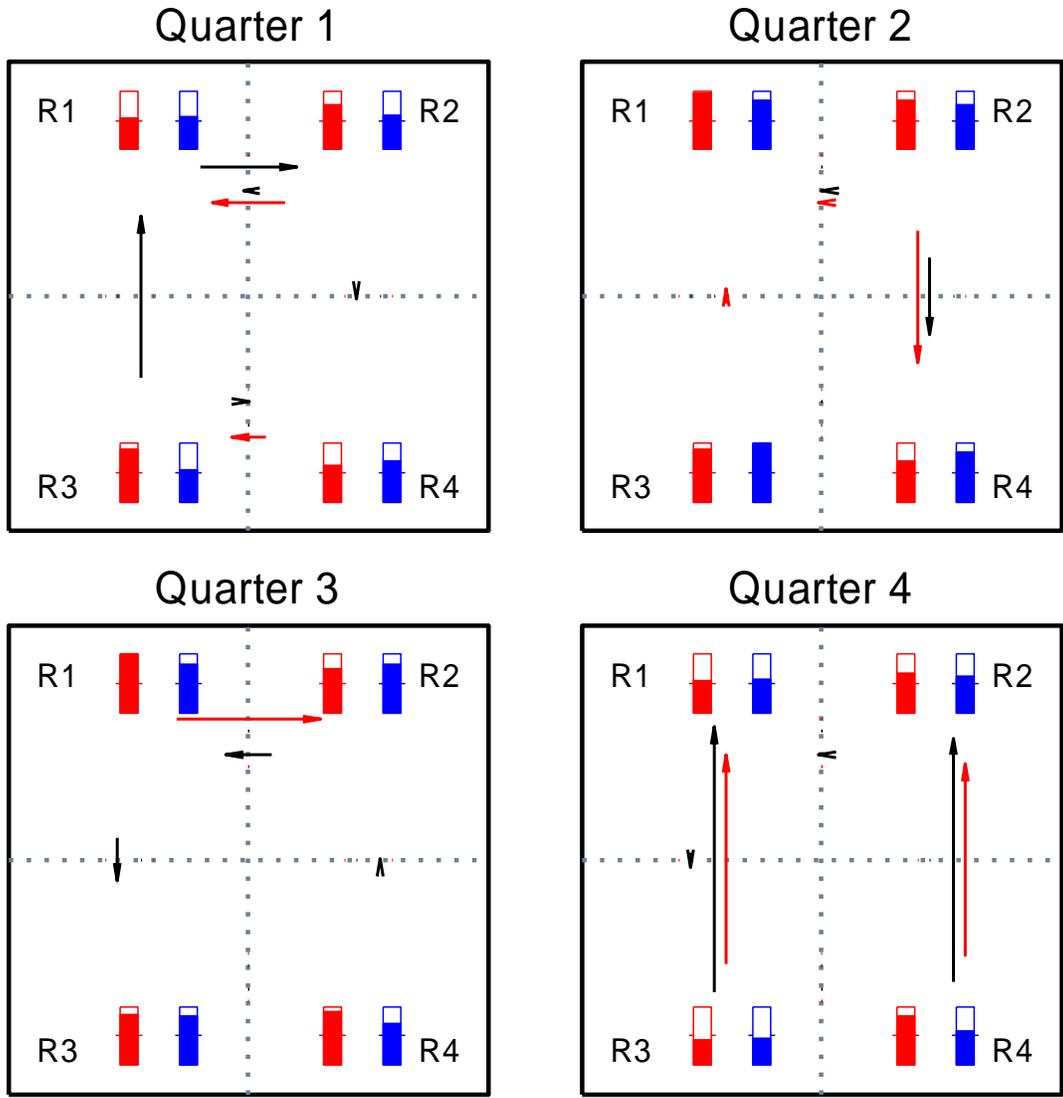


Figure 14. Estimated quarterly movement coefficients from the four-region model excluding (black arrows) and including (red arrows) seasonal catchability coefficients and seasonal catchability coefficients from the four-region and one-region models (red and blue “thermometers”, respectively). The movement coefficient is proportional to the length of the arrow. The maximum movement (quarter 4, region 3 to region 1) represents movement of 45% of the fish at the start of the quarter. The “thermometers” are a representation of the relative seasonal catchability for the Taiwanese longline fleet by region and quarter. The proportion of the thermometer that is filled is relative to the maximum seasonal catchability coefficient. The blue thermometers are the equivalent representation of the seasonal catchability coefficients from the single-region model.

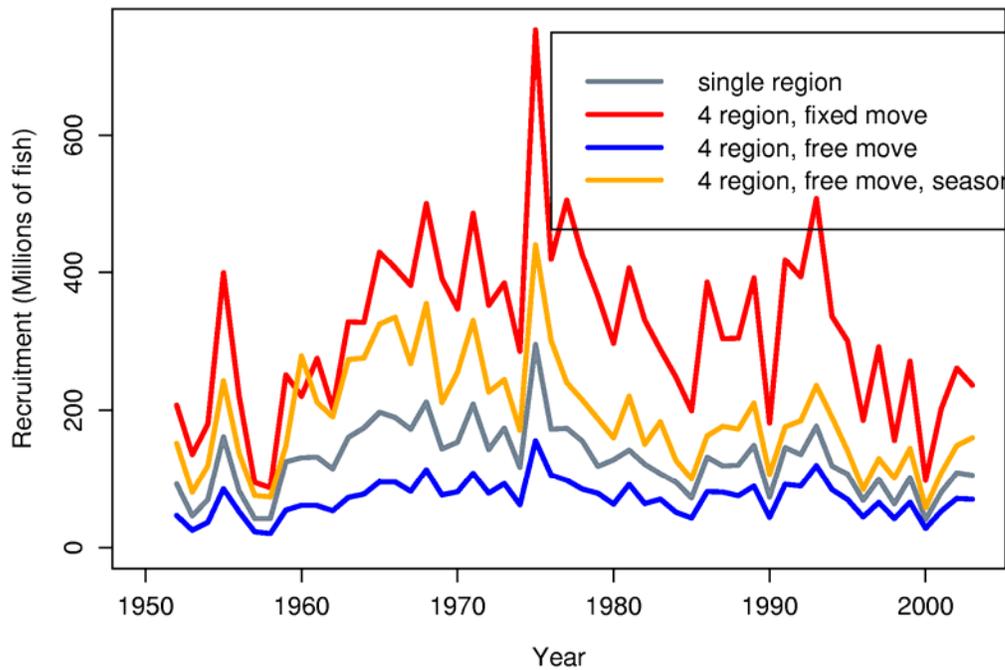
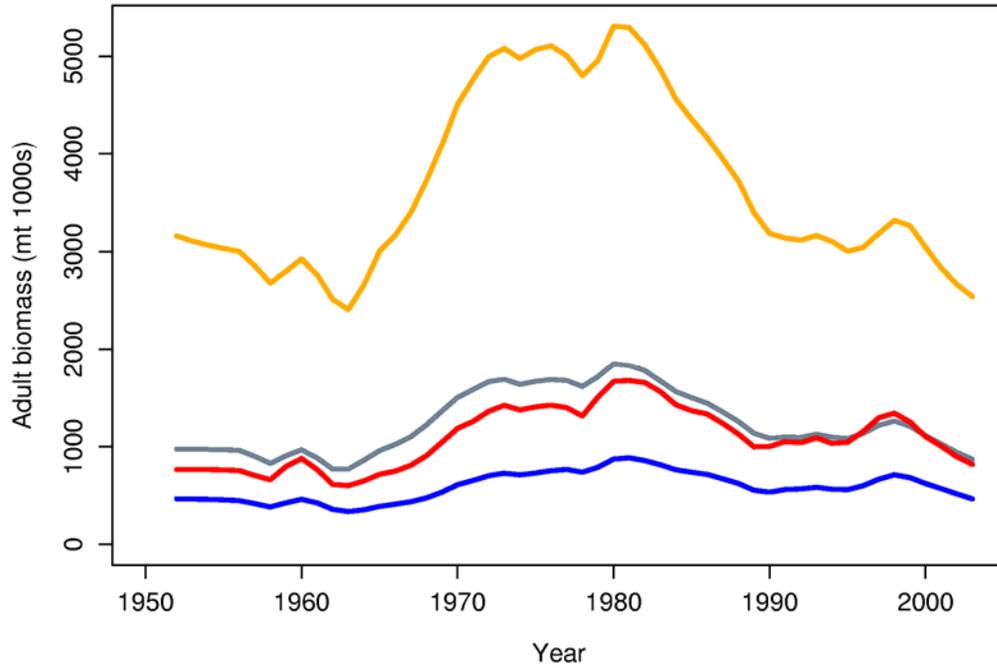


Figure 15: A comparison of the annual trends in adult biomass and recruitment from the single region and four region models with fixed movement (fix move), and estimated movement without (free move) and with (free move, seasonal q) the estimation of seasonal catchability coefficients.

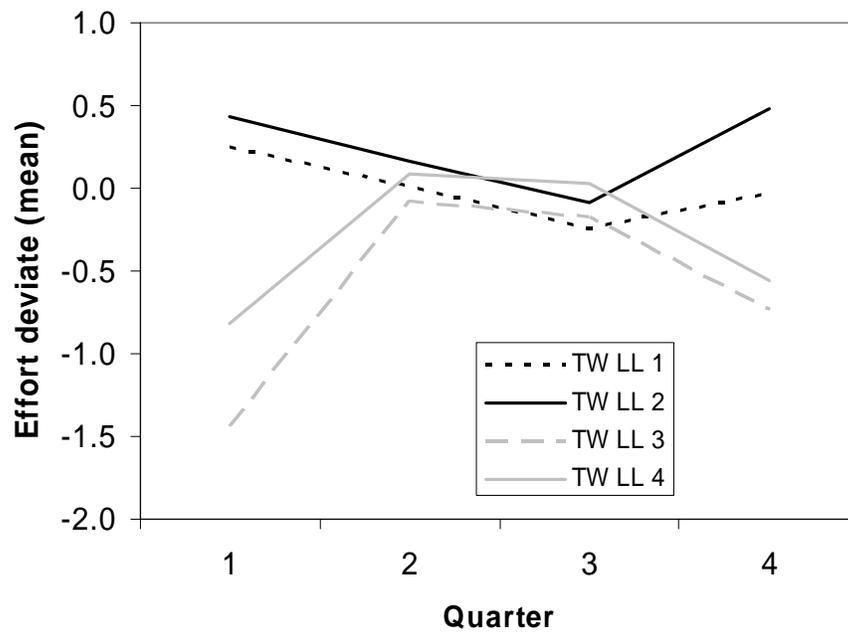


Figure 16. Quarterly average effort deviates for the region specific Taiwanese longline fisheries included in the four-region, fixed movement model.

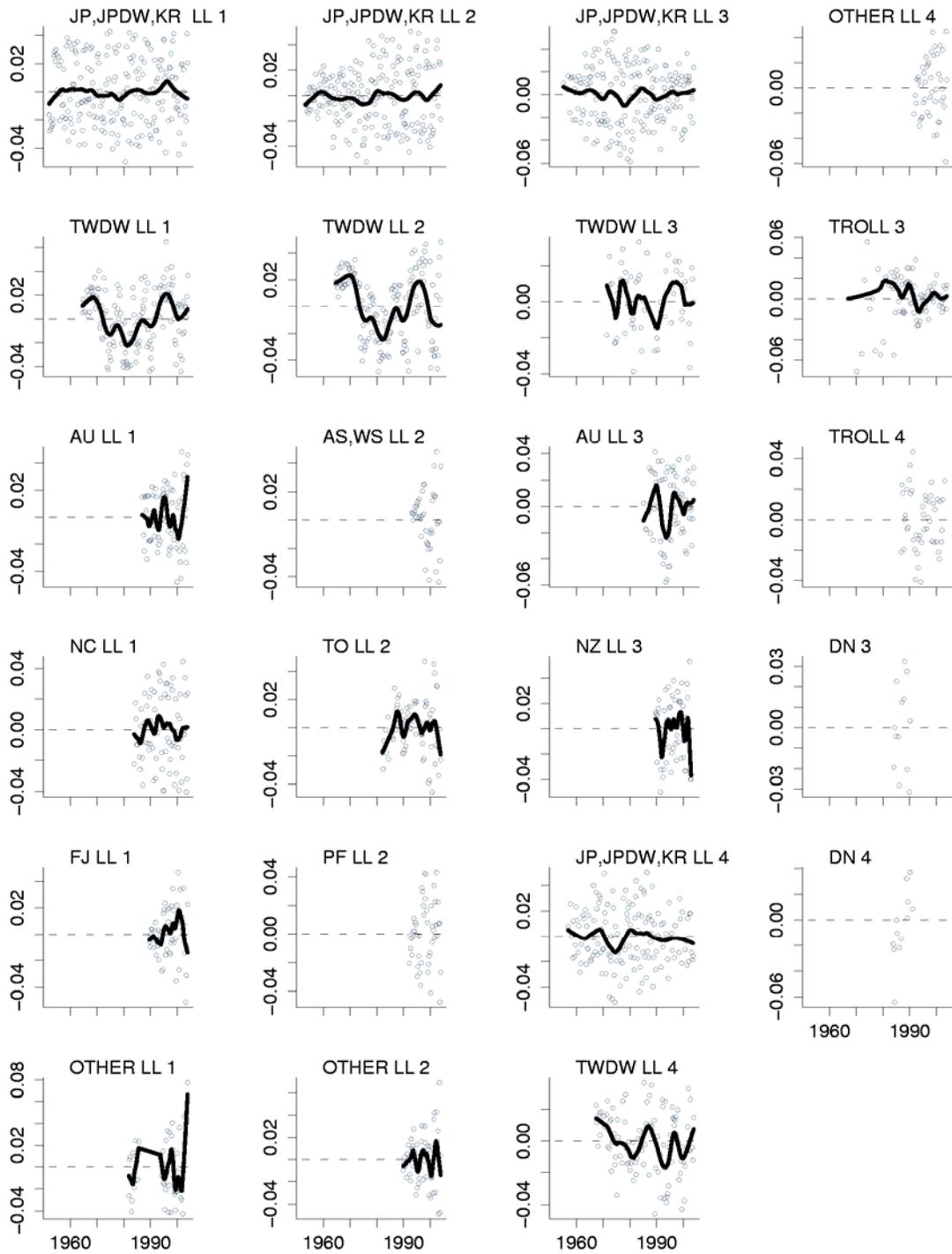


Figure 17: Residuals of \ln (total catch) for each fishery. The solid line represents a lowest fit to the data.

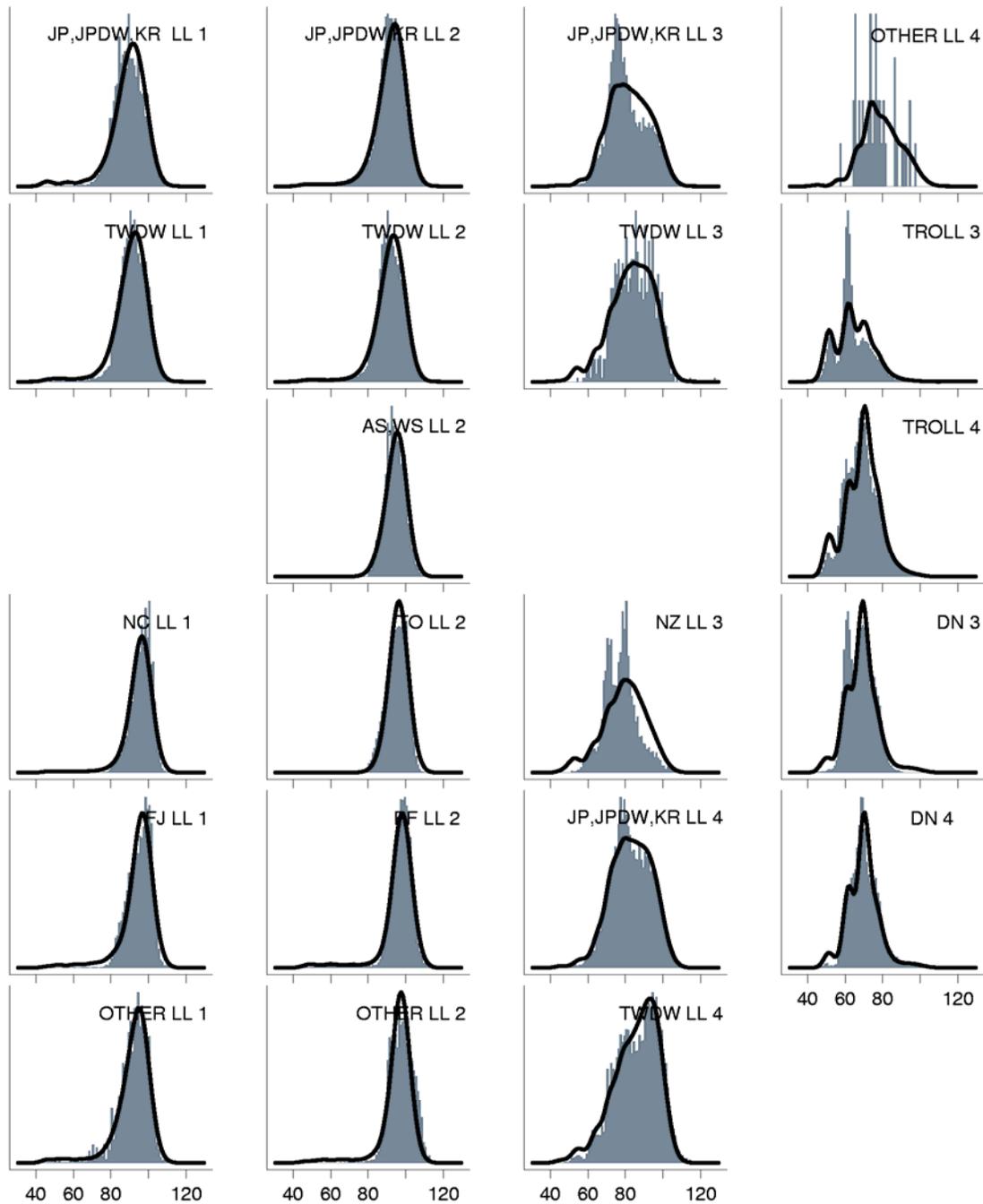


Figure 18: Observed (histograms) and predicted (line) length frequencies (in cm) for each fishery aggregated over all time periods. Fisheries not plotted have no associated length frequency data.

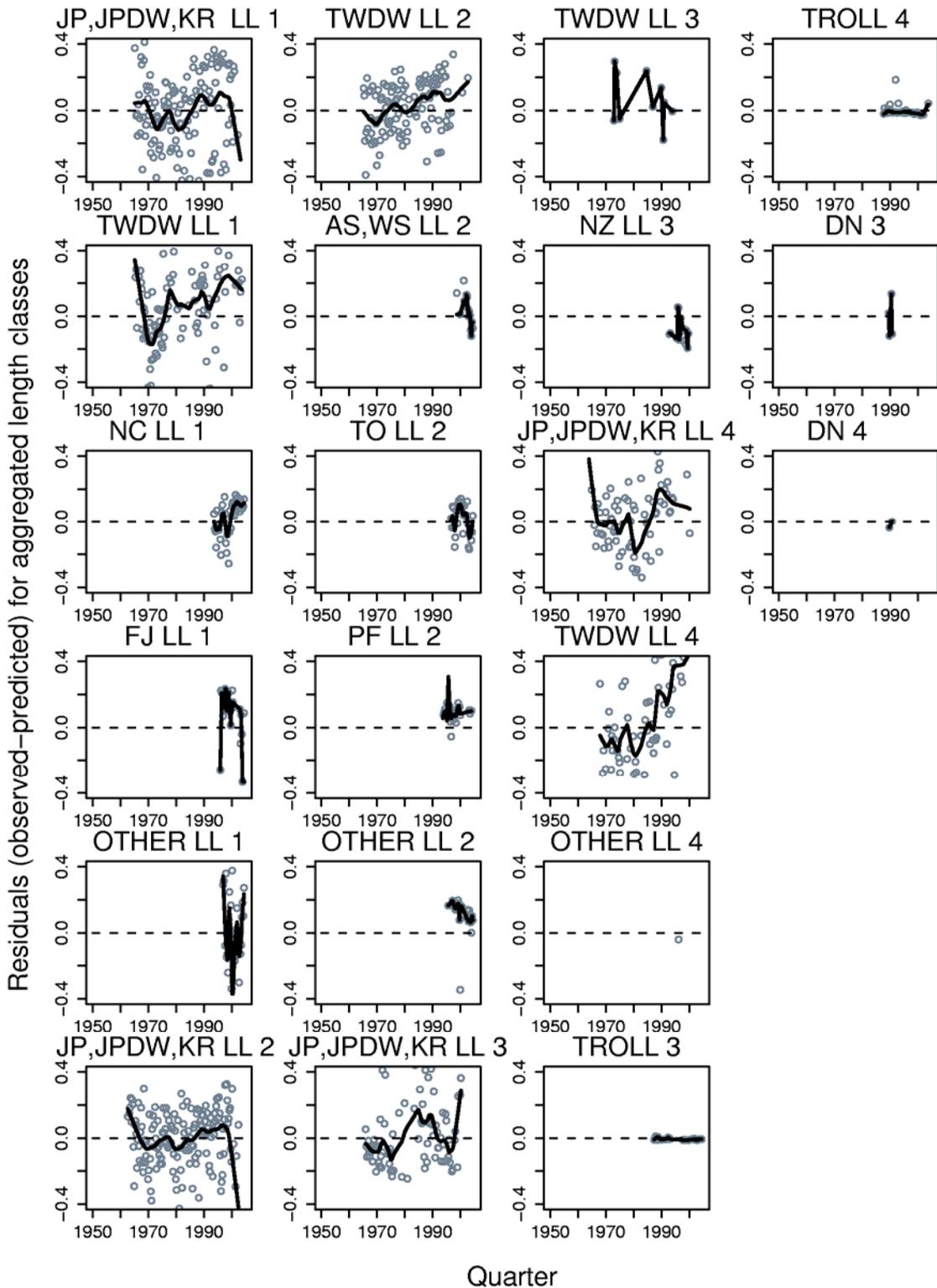


Figure 19: Residuals (observed – predicted) of the aggregated proportion of fish in the larger length classes from sampled and predicted catches by fishery and sample period. The aggregated length range is 90–120 cm for all the longline fisheries and 70–90 cm for all other fisheries. The line represents a lowess smoothed fit to the data.

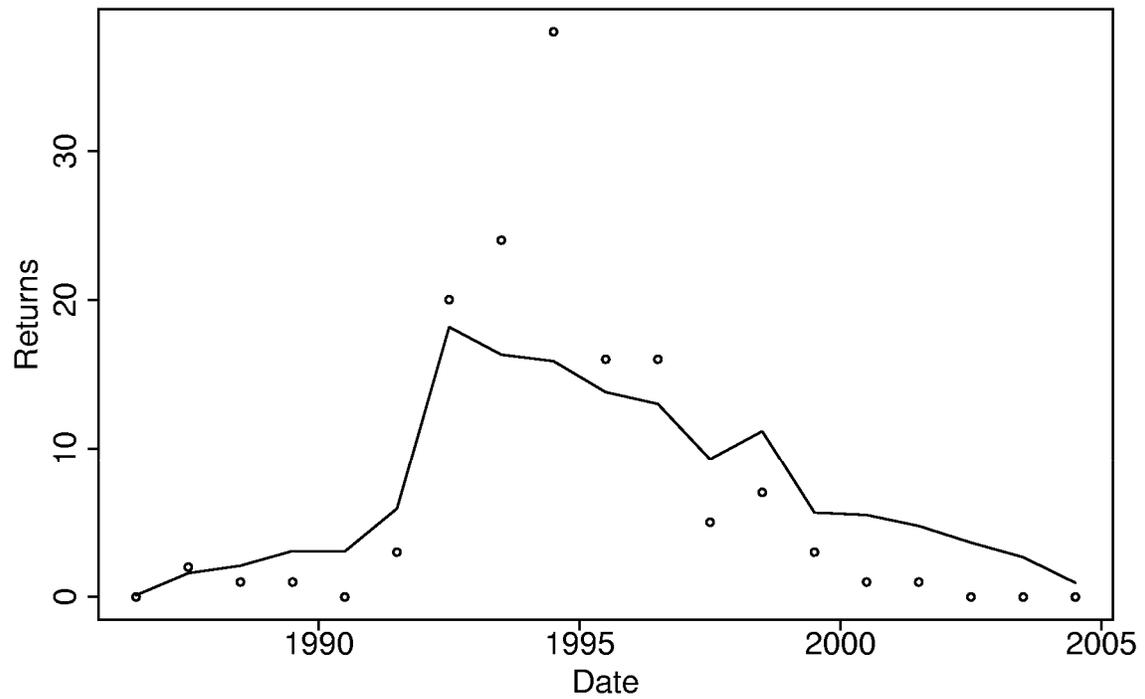


Figure 20: A comparison of observed (points) and predicted (line) number of annual tag returns from the south Pacific albacore fishery.

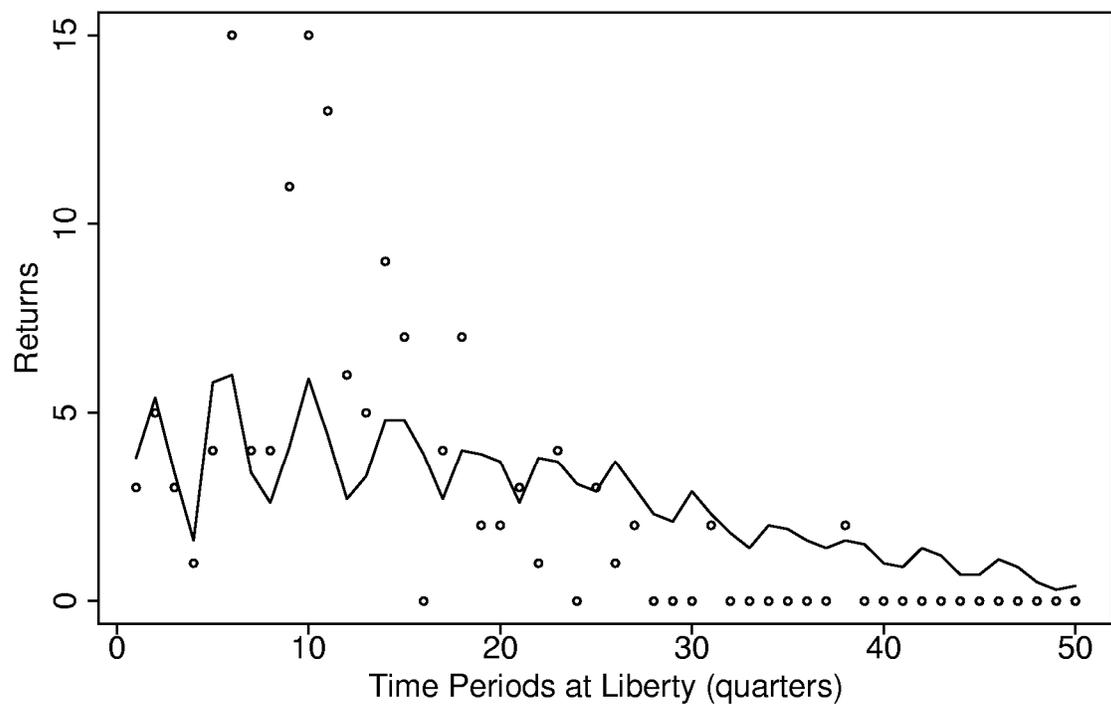


Figure 21: A comparison of observed (points) and predicted (line) number of tag returns by period at liberty (quarters) from the south Pacific albacore fishery.

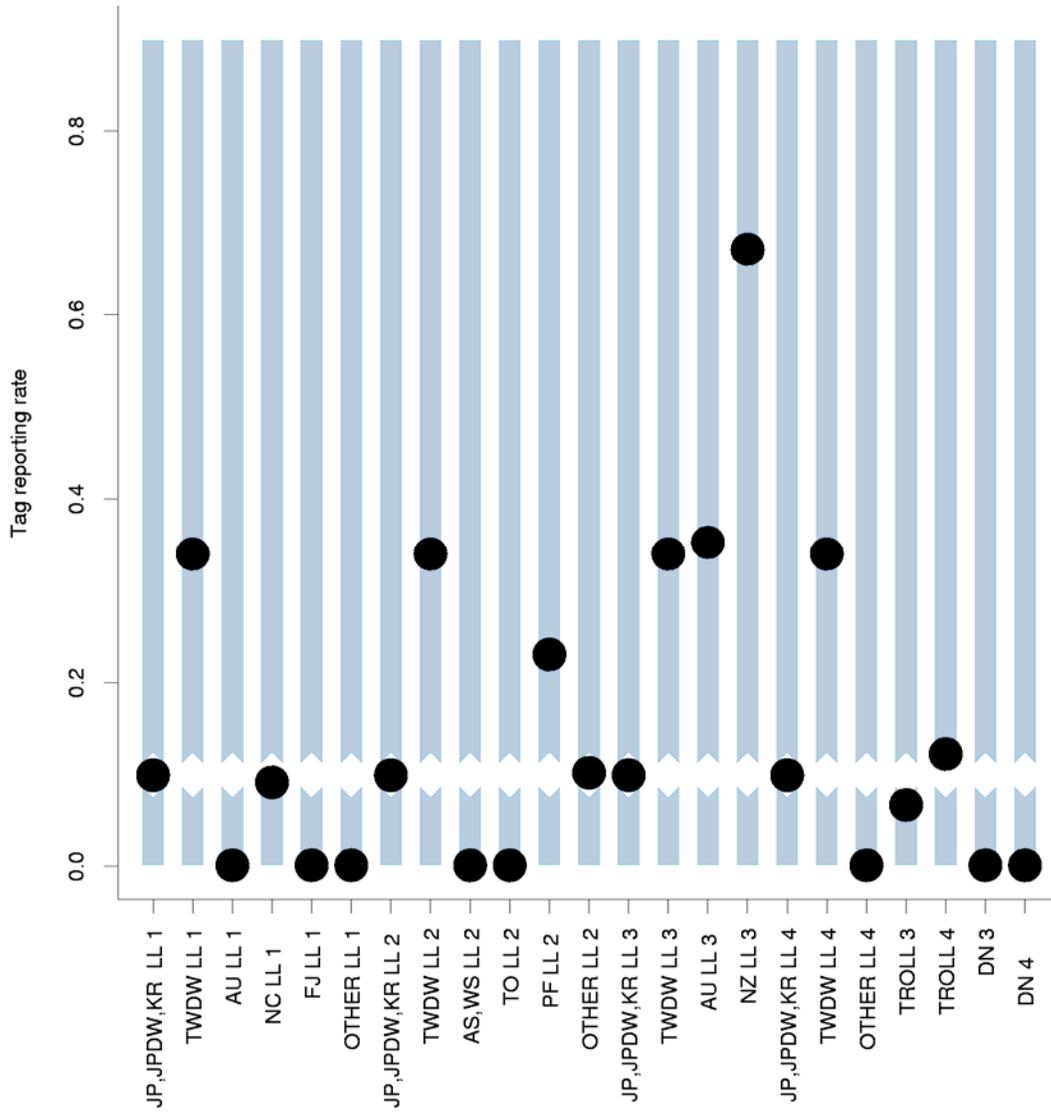


Figure 22: Estimated tag-reporting rates by fishery (black circles). The white diamonds indicate the modes of the priors for each reporting rate and the grey bars indicate a range of ± 1 SD.

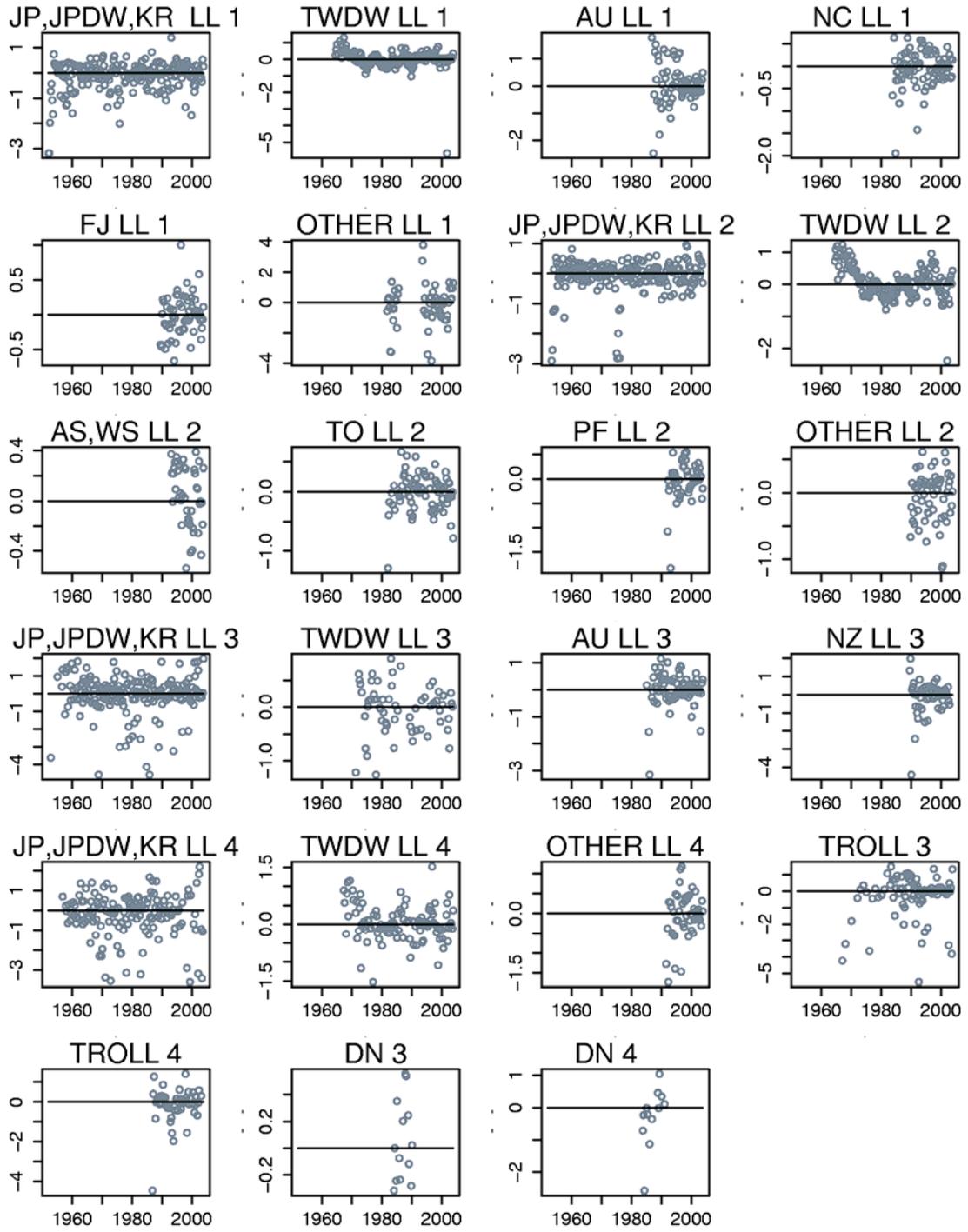


Figure 23: Quarterly effort deviates by fishery.

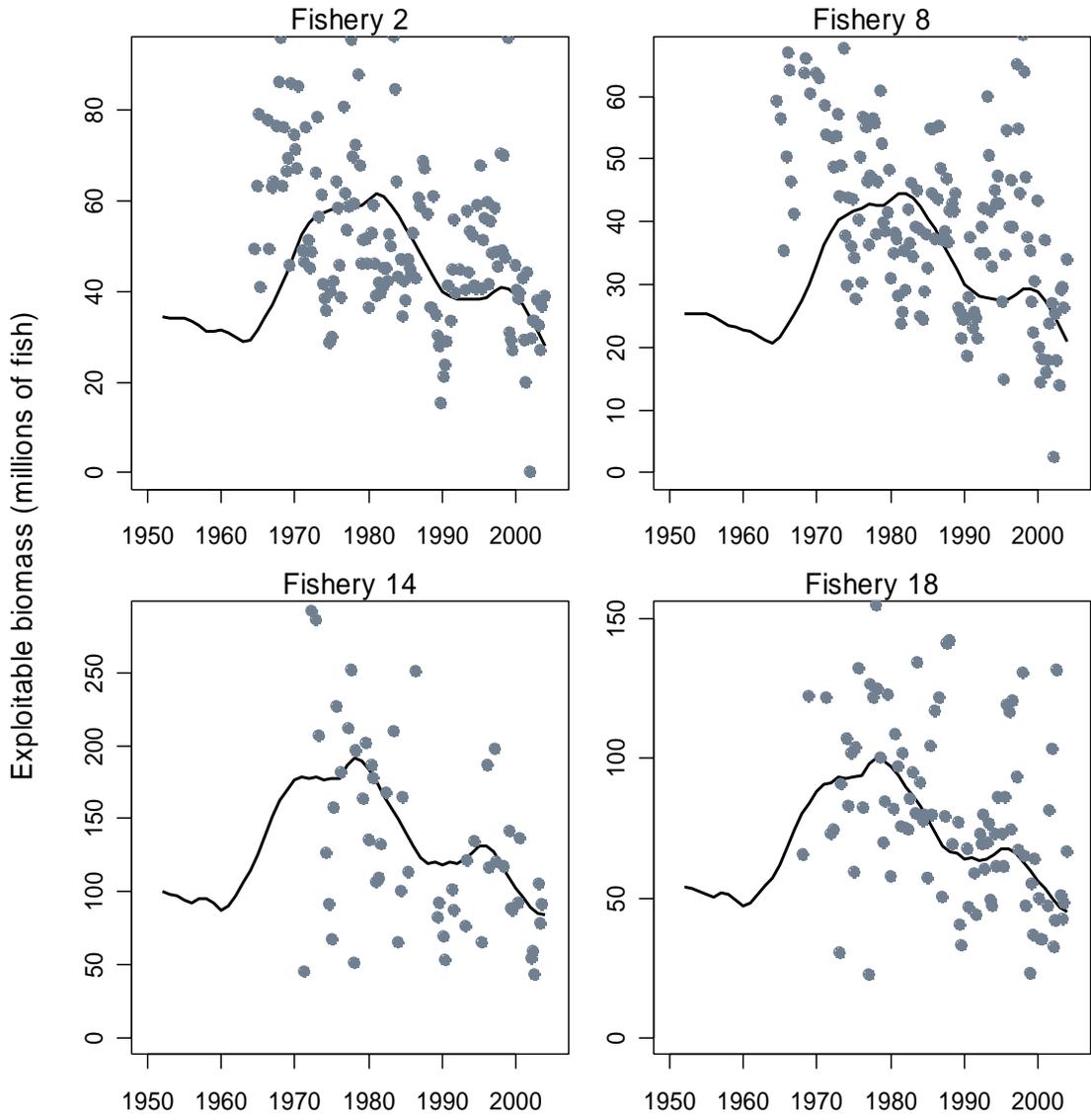


Figure 24: A comparison of the annual exploitable biomass (number of fish) (line) and the predicted exploitable biomass from the quarterly observations of catch and effort from each of the Taiwanese longline fisheries (observed catch/(effort * seasonal catchability)) (points).

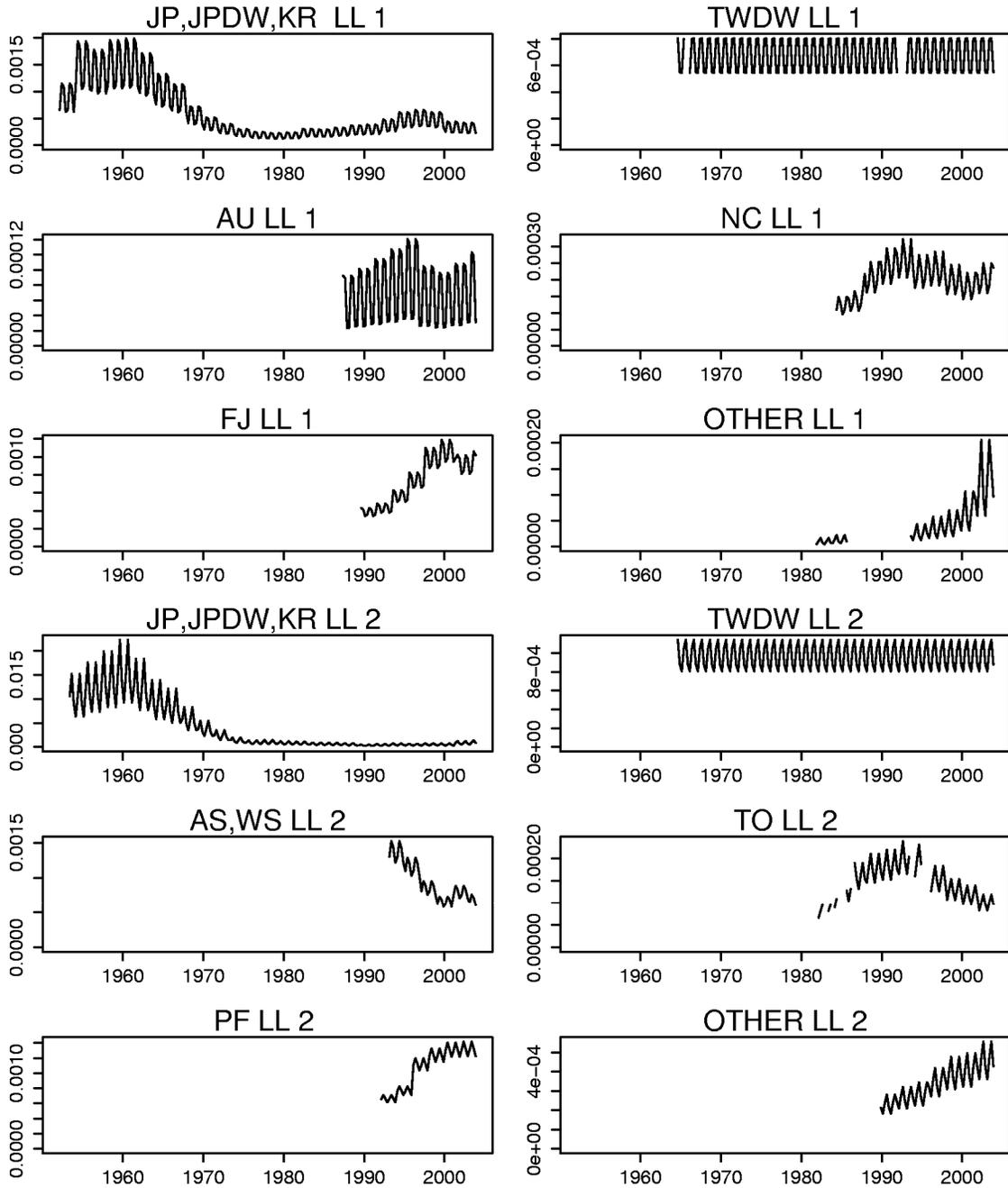


Figure 25a: Quarterly trends in catchability by fishery from the single region model.

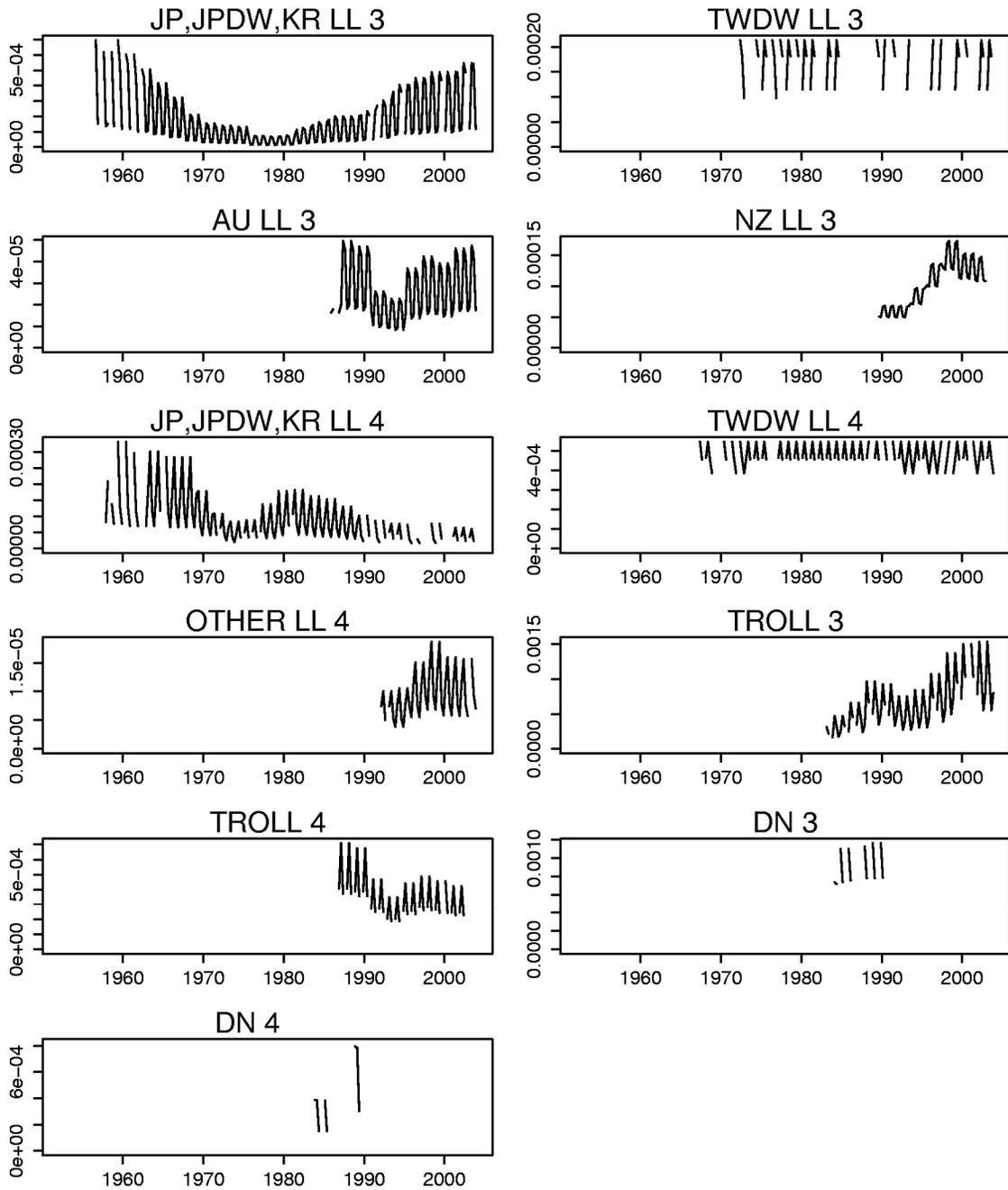


Figure 25b: Quarterly trends in catchability by fishery from the single region model.

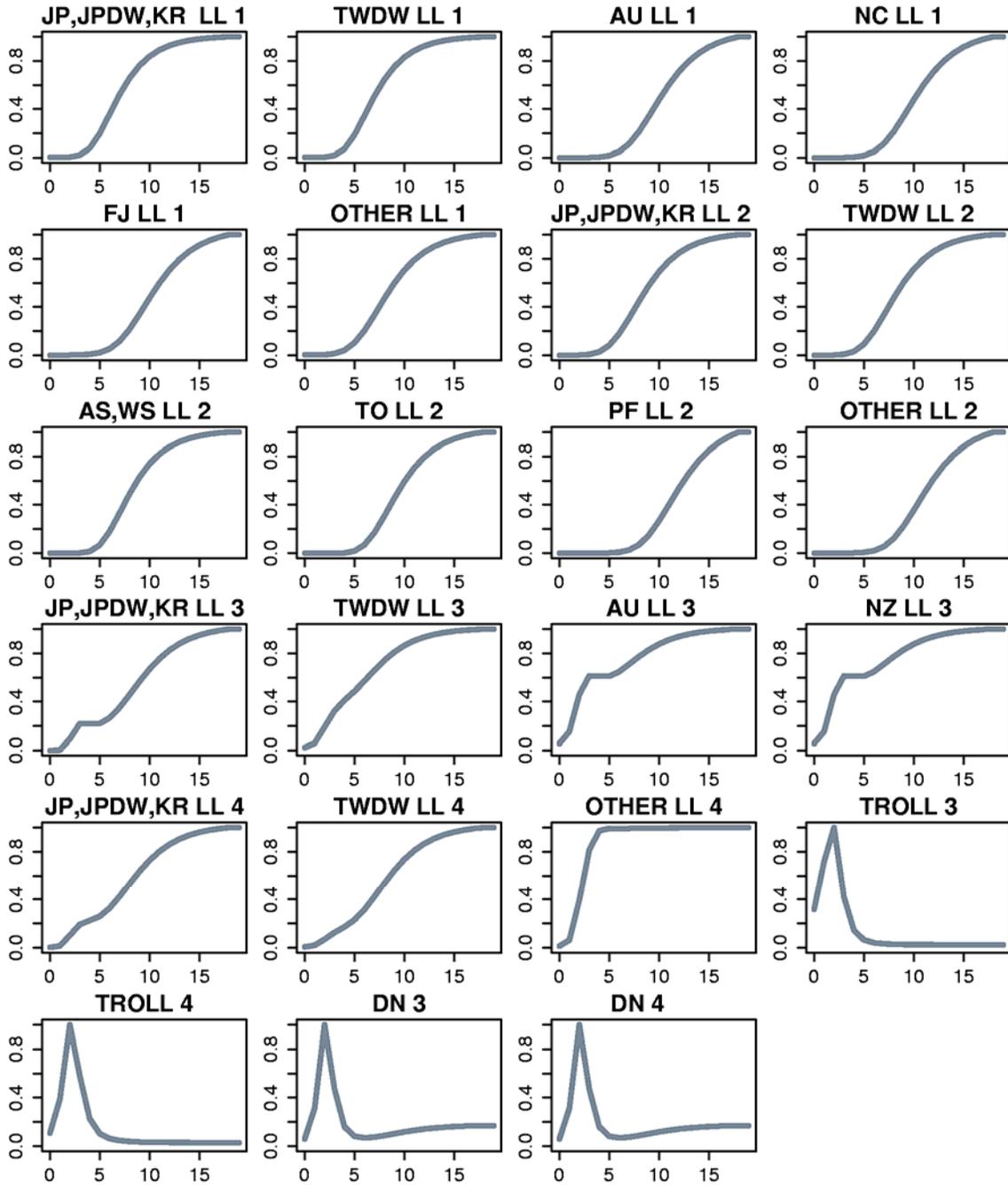


Figure 26: Selectivity at age (years) by fishery from the single region model.

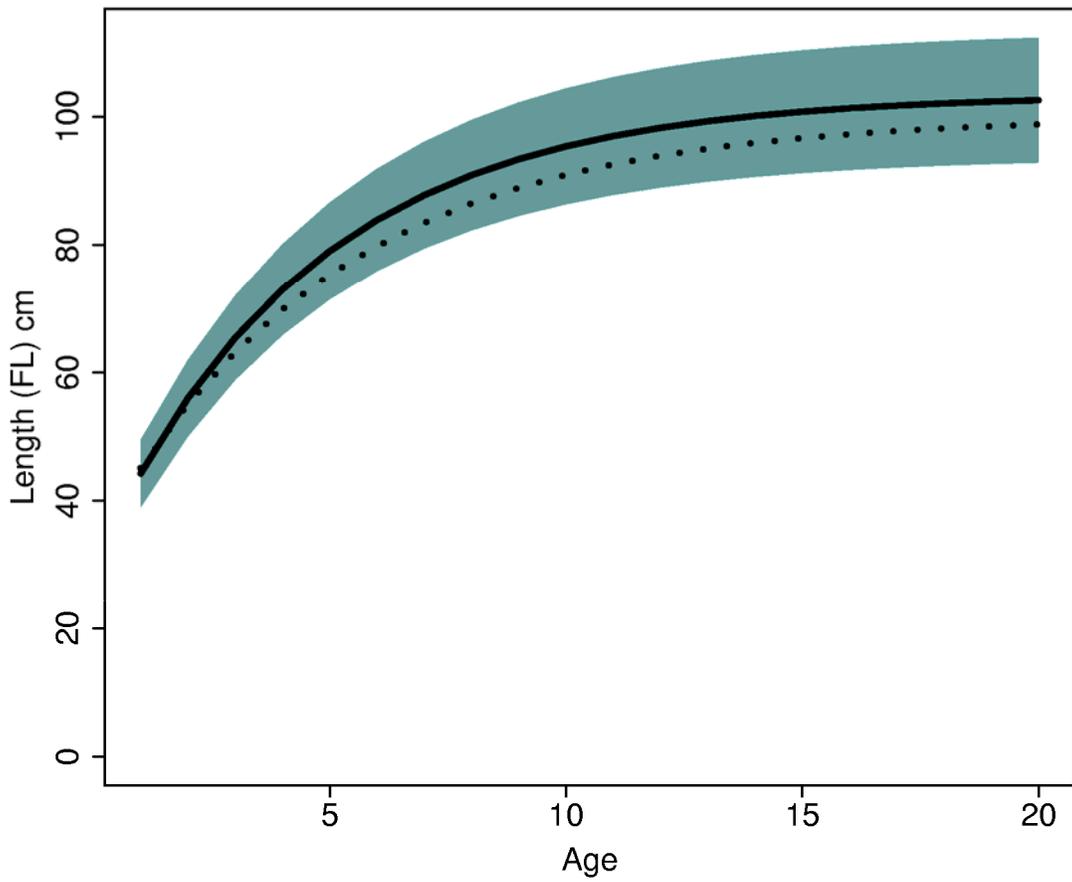


Figure 27: The estimated length (fork length) at age (years) (solid line) and the 95% confidence interval. The dashed line represents the initial values included in the model from the von Bertalanffy parameters.

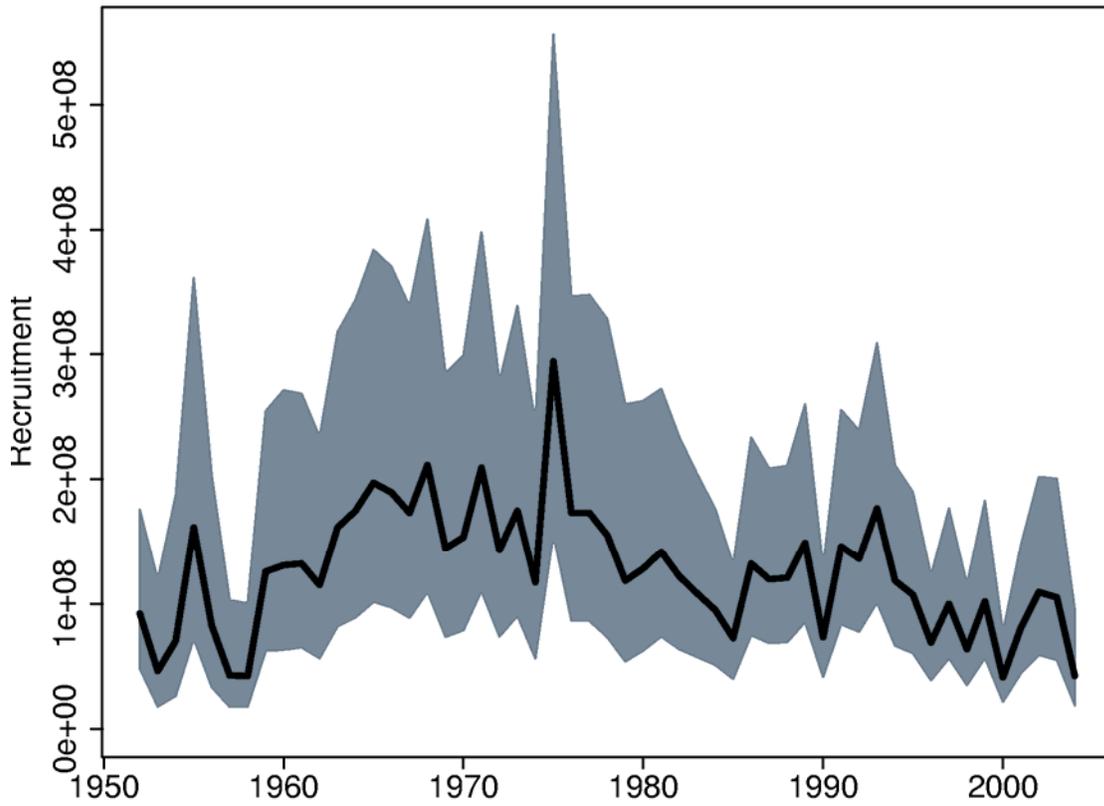


Figure 28: Annual recruitment (number of fish) estimates from the one region model. The shaded area indicates the approximate 95% confidence intervals.

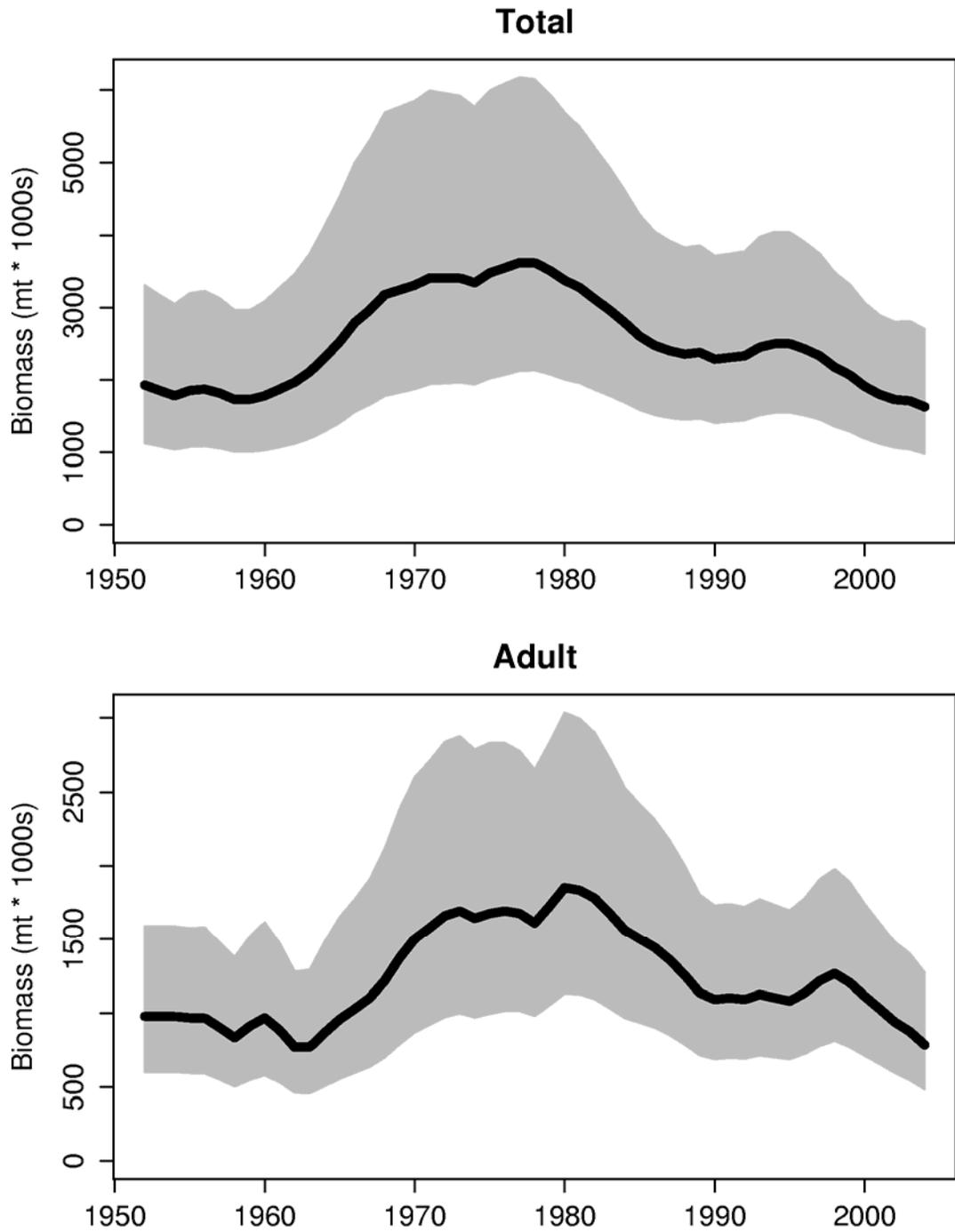


Figure 29: Annual estimates total (top) and adult (bottom) biomass (thousands of metric tonnes) from the one region model. The shaded area indicates the approximate 95% confidence intervals.

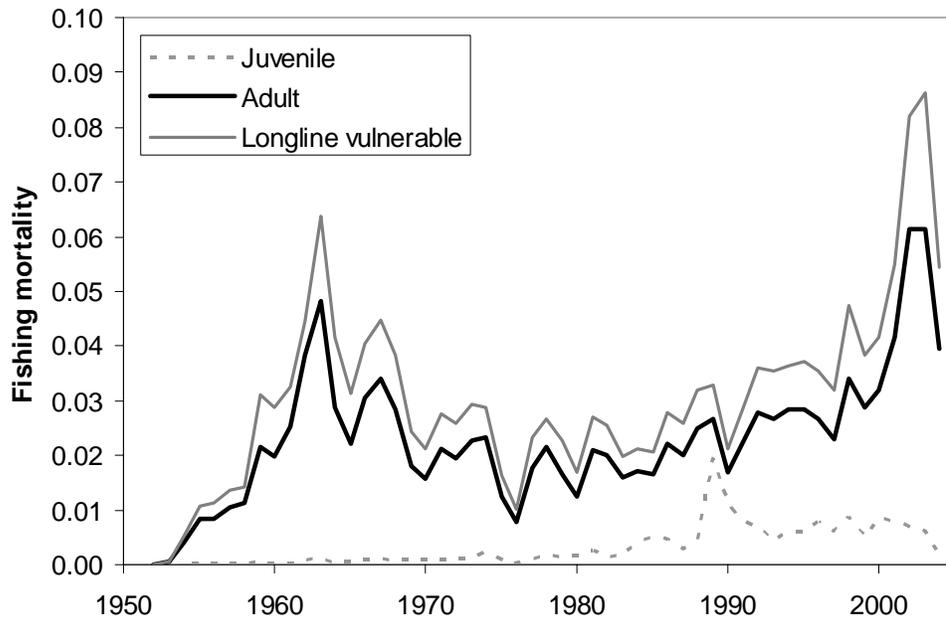


Figure 30: Annual estimates of fishing mortality for juvenile, adult and longline vulnerable south Pacific albacore from the one region model.

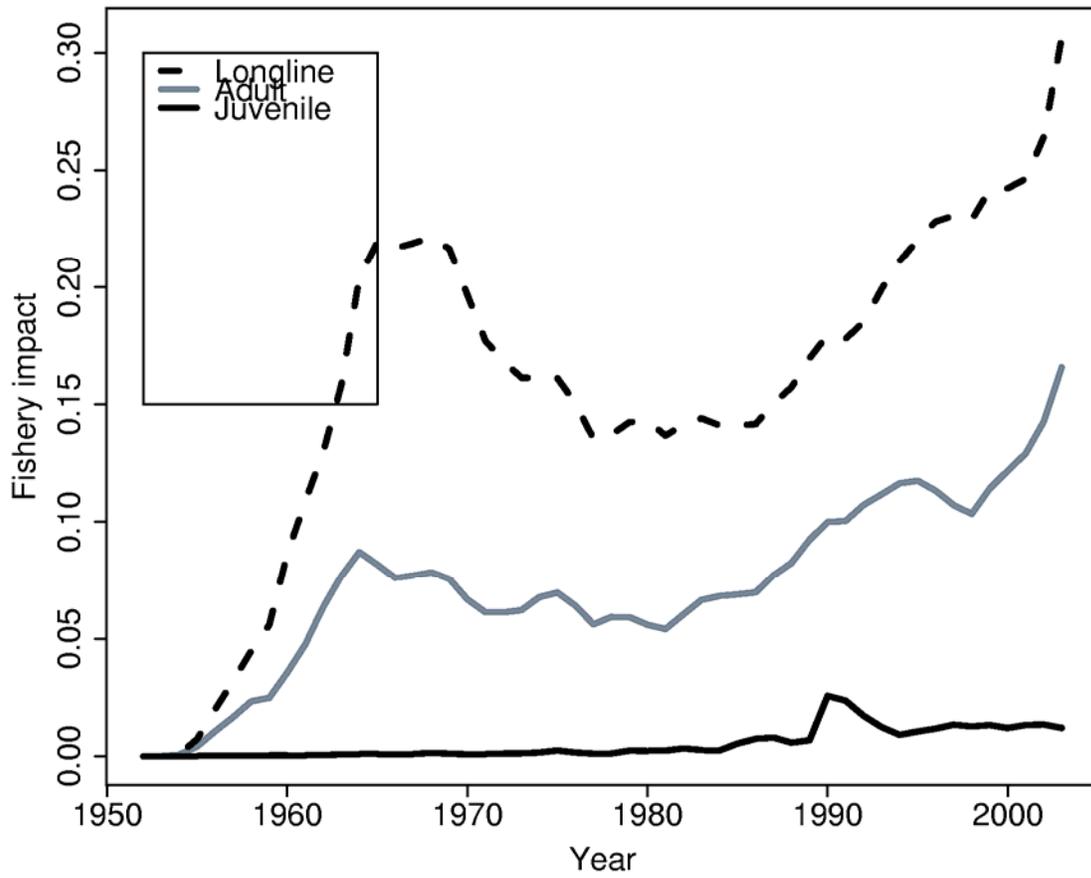


Figure 31: The estimated fishery impact on juvenile and adult biomass and longline exploitable biomass (proportional reduction in biomass attributable to fishing) from the one region model.

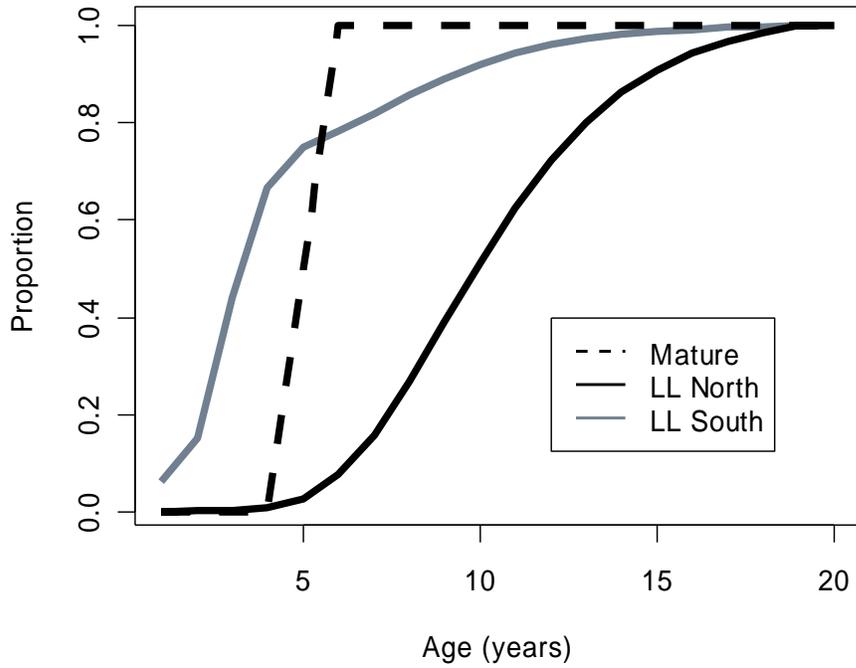


Figure 32: A comparison of the average selectivities at age for the northern and southern longline fisheries and the proportion mature at age assumed in the model.

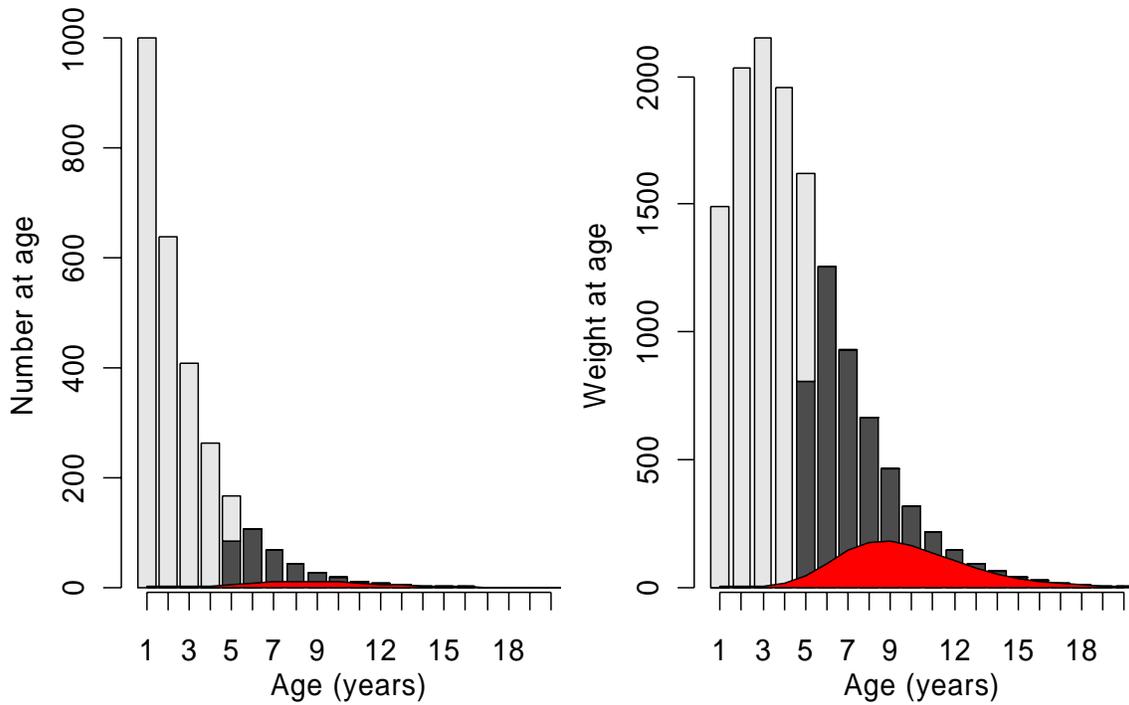


Figure 33: The composition of a theoretical cohort (numbers at age and weight at age); immature (light grey), mature (dark grey) and vulnerable to the northern longline fishery (red).

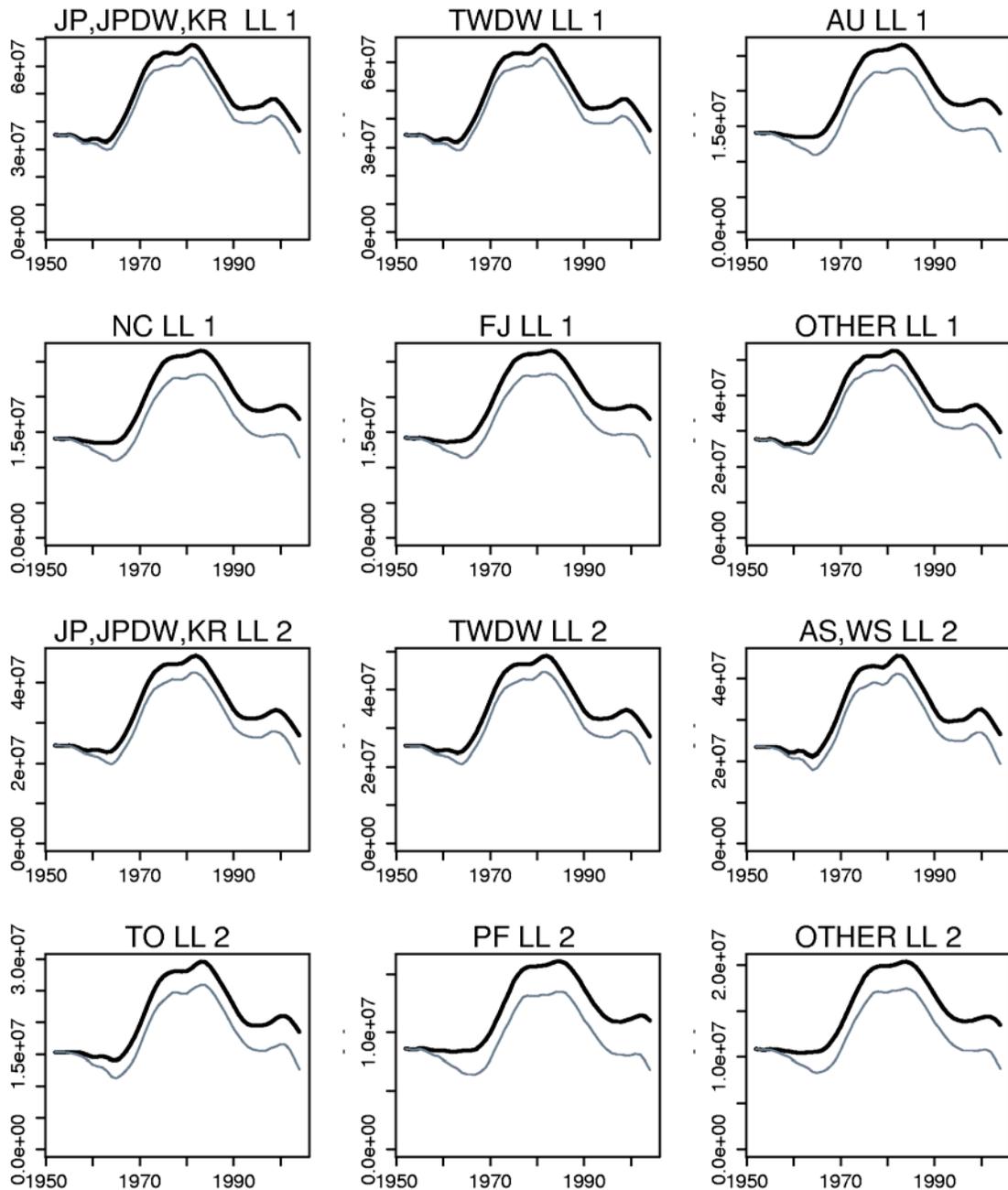


Figure 34a: A comparison of the annual level of exploitable biomass for individual fisheries (grey line) and the level of exploitable biomass predicted in the absence of fishing (black line). The difference between the two lines is attributable to the impact of all fishing on the exploitable biomass available to the fishery. Biomass is presented in numbers of fish for all fisheries except the drift net fisheries (mt).

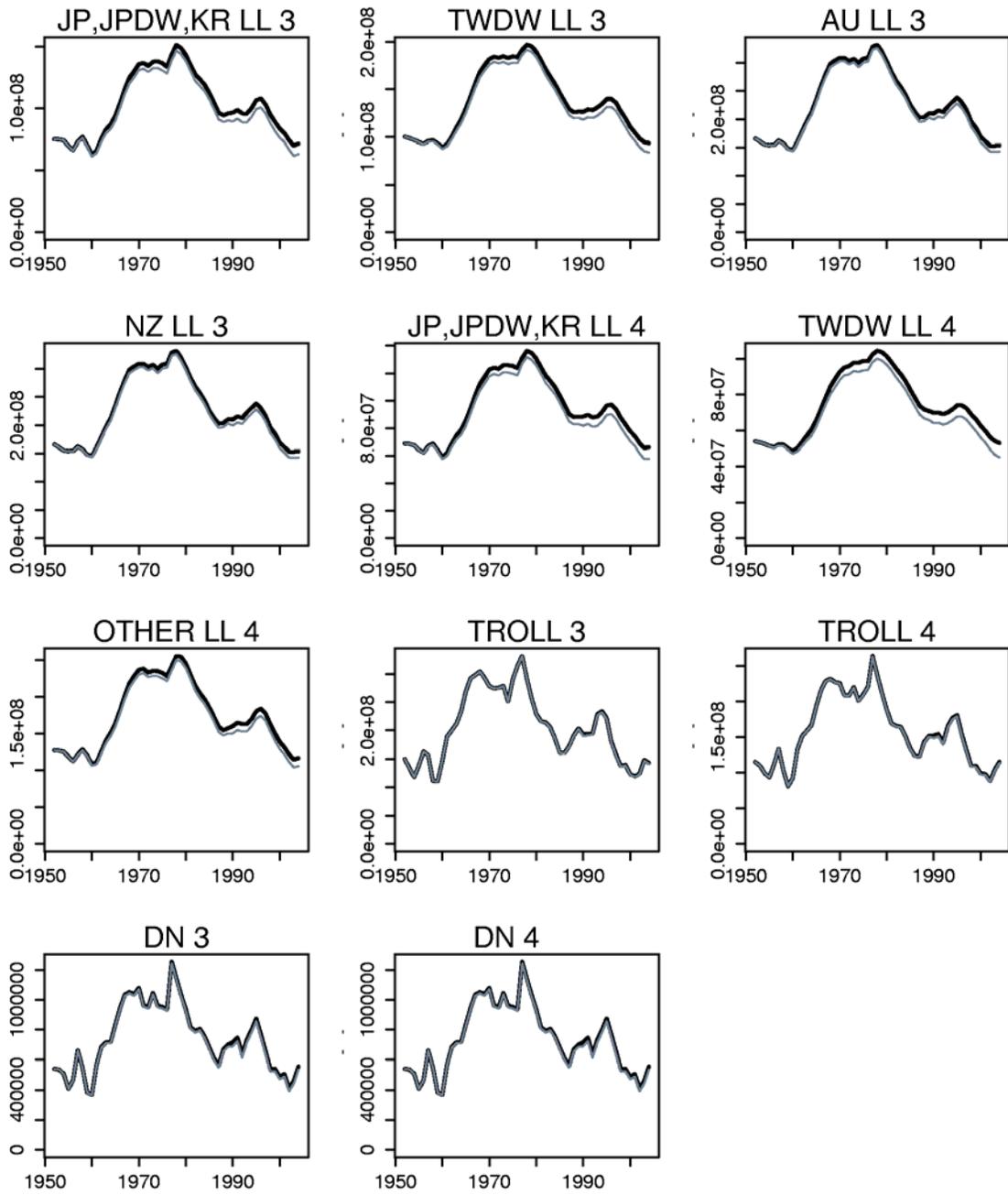


Figure 34b. Continued.

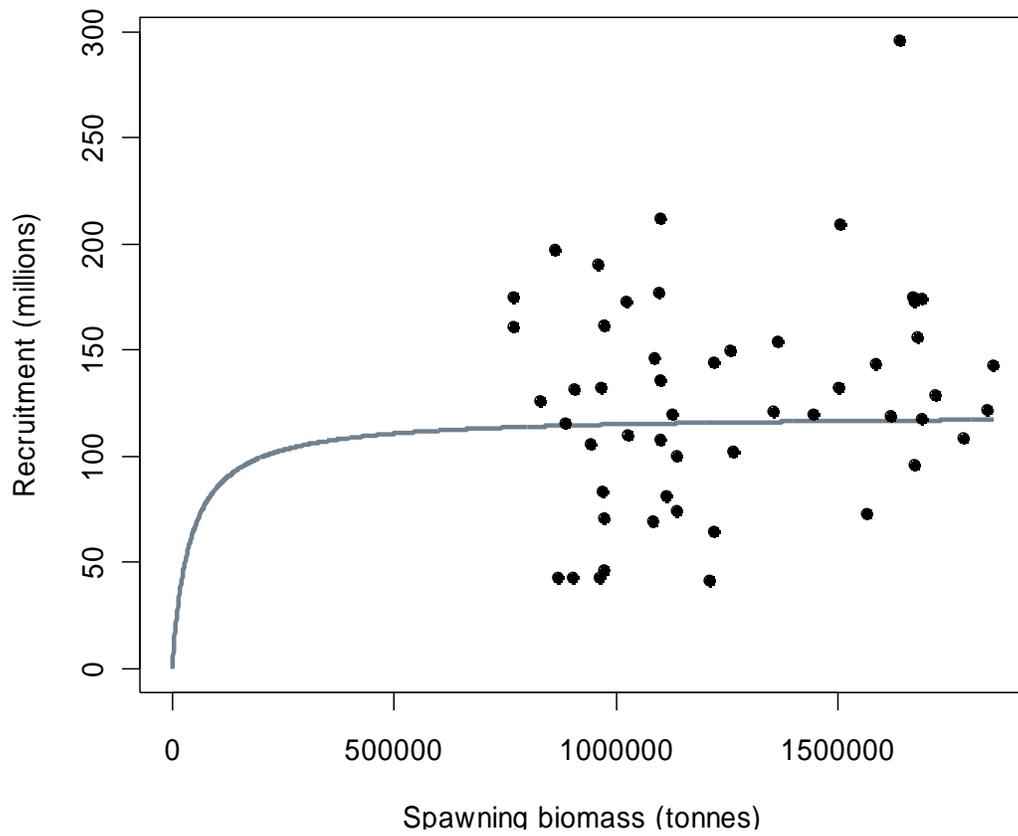


Figure 35. Spawning biomass – recruitment estimates and the fitted Beverton and Holt stock-recruitment relationship (SRR).

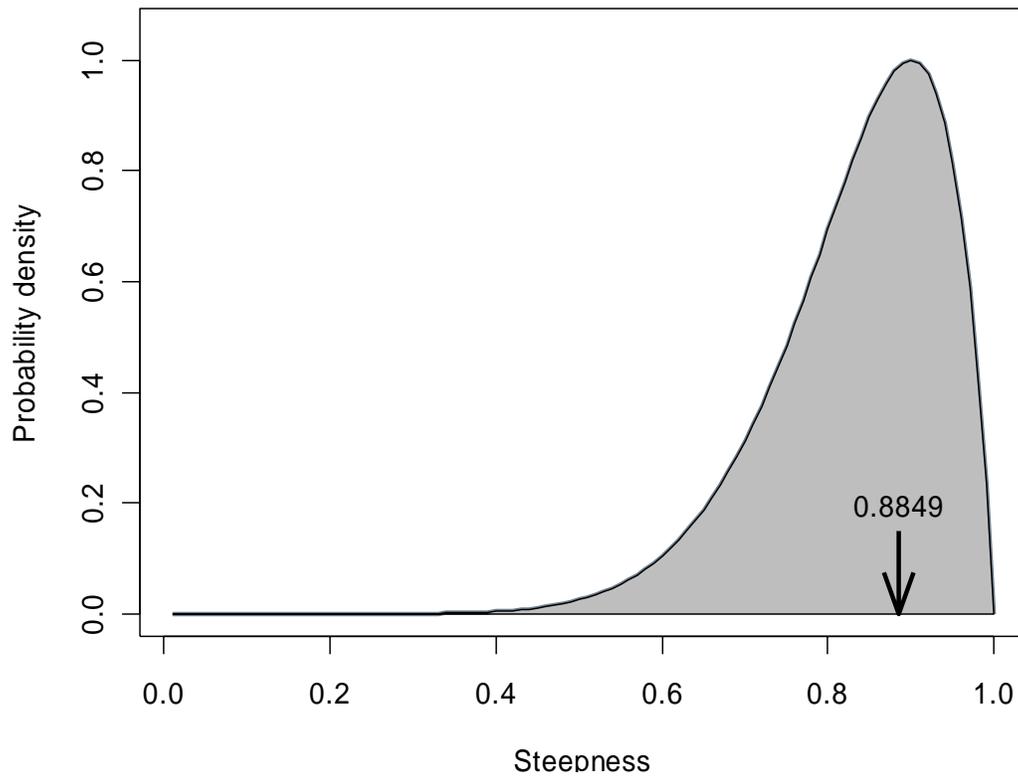


Figure 36. The probability density distribution for the prior on steepness and the resulting model point estimate of steepness; prior distributions mode = 0.9, stdev= 0.1.

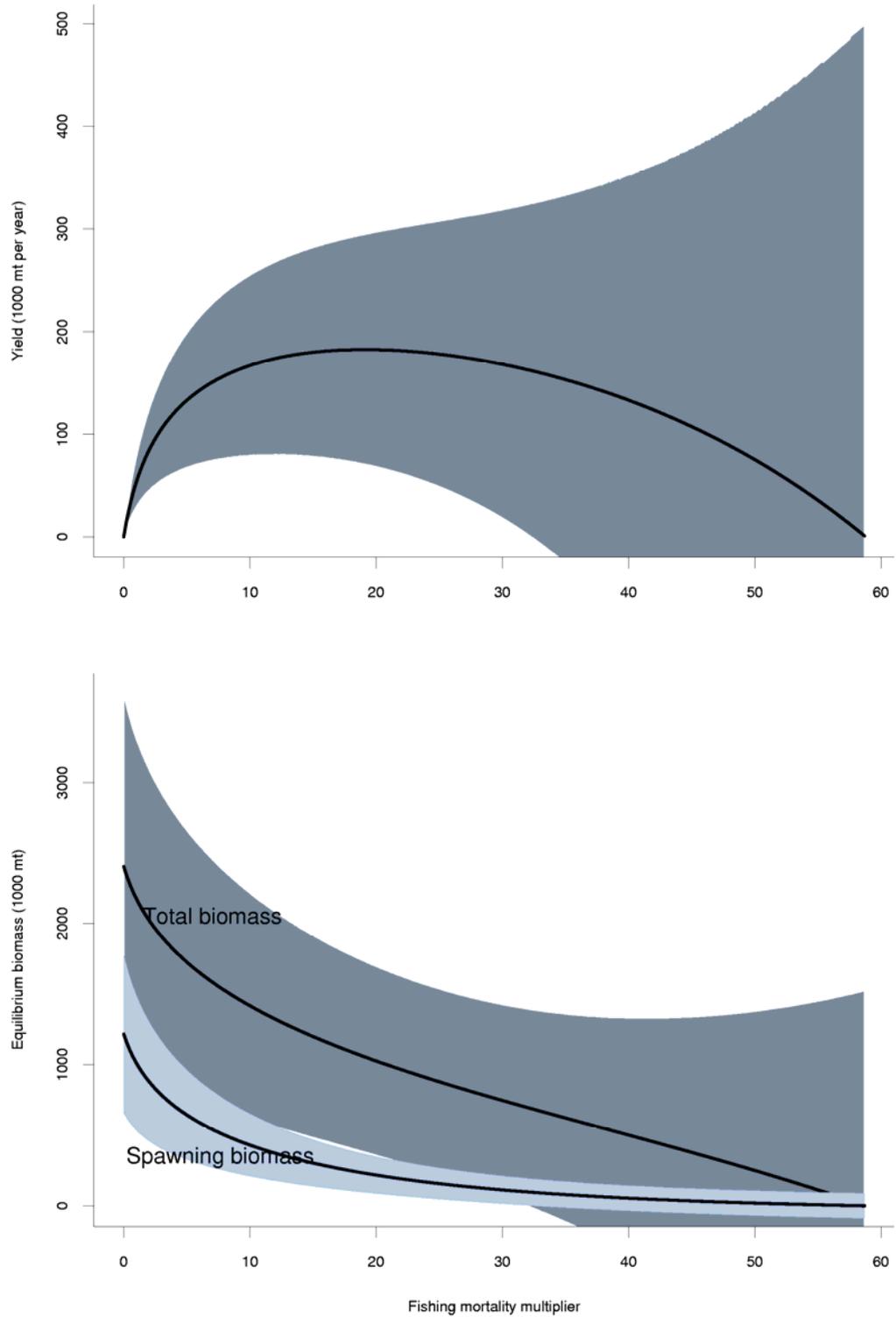


Figure 37: Yield, equilibrium biomass and equilibrium spawning biomass as a function of fishing mortality multiplier. The shaded areas represent approximate 95% confidence intervals.

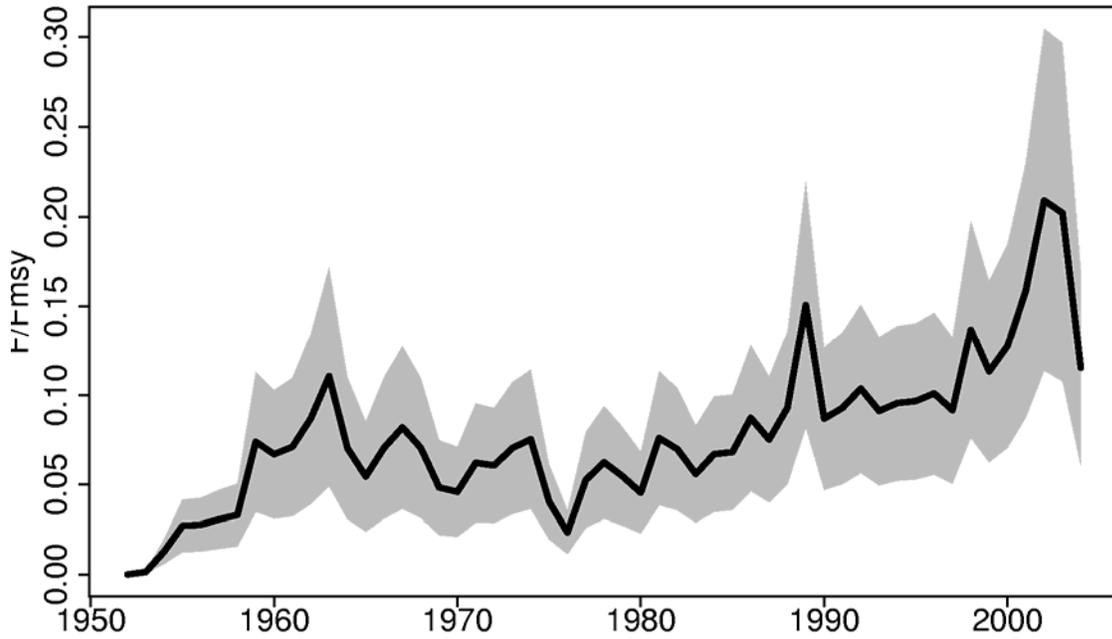


Figure 38: Annual exploitation rate (E) as a proportion of the exploitation rate at MSY (E_{MSY}). The grey area represents the 95% confidence interval.

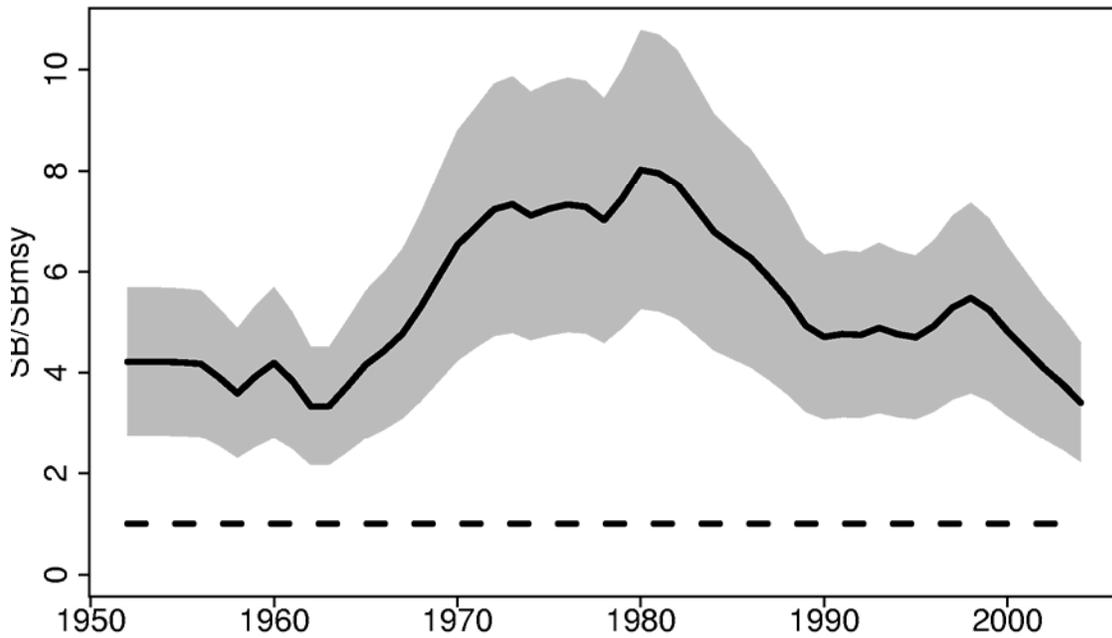


Figure 39: Annual adult biomass (SB) relative to the adult biomass at MSY (SB_{MSY}). The grey area represents the 95% confidence interval.