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STOCK ASSESSMENT OF ALBACORE TUNA IN THE SOUTH PACIFIC OCEAN

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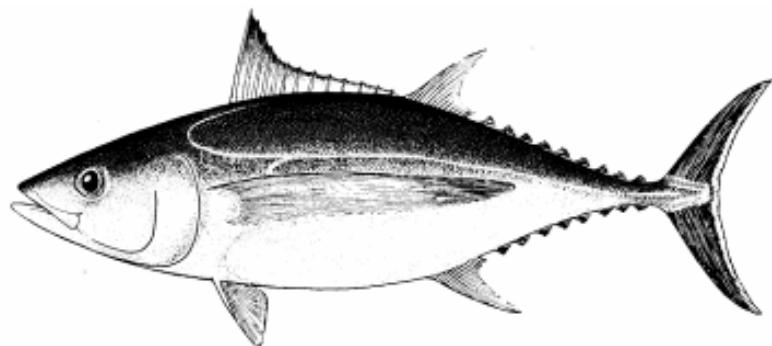
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1   Executive Summary

This paper presents the current stock assessment of albacore tuna (*Thunnus alalunga*) in the south Pacific Ocean, carried out using MULTIFAN-CL.

Since the last assessment, many of the underlying structural assumptions of the model have been reviewed. Major changes to model structure include: moving the central latitudinal boundary north by 5° to 25°S; separating data from the Japanese and Korean longline fisheries; including standardised CPUE data as relative abundance indices for the Japanese, Korean and Chinese Taipei longline fisheries, and the New Zealand troll fishery; reducing the weight given to length frequency data; making the selectivity of longline fisheries seasonal; removing length frequency data collected in Pago Pago before 1971; changing the biological parameters for natural mortality and reproductive potential; reducing the influence of CPUE from non-standardized fisheries; and permitting declining (i.e. dome-shaped) selectivity to be estimated for most longline fisheries.

The cumulative effect of these changes was to reduce the biomass estimates and raise the fishing mortality estimates compared to previous assessments. Model diagnostics indicate that some sources of bias have been removed, but that problems remain.

Lower levels of stock size and MSY than in previous assessments appear to be more realistic, since many sources of potential bias have been removed. However, given the evidence of remaining bias, there is considerable uncertainty about current levels of fishing mortality. The stock status indicator $F_{2004-2006}/F_{MSY}$ is strongly affected by structural uncertainty in the model, some of it related to the failure to model the increasing length of fish selected (selectivity) by the fishery through time, and some related to uncertainty about whether the recent large decline in standardized Chinese Taipei CPUE accurately reflects a decline in biomass.

Models that permit selectivity to vary through time tend to give lower biomass relative to B_{MSY}, and higher fishing mortality relative to F_{MSY}, throughout the time series. On the other hand, models that give less weight to the recent decline in Chinese Taipei CPUE tend to estimate higher biomass relative to B_{MSY}, and lower fishing mortality relative to F_{MSY}, in recent years.

Estimates of $F_{2004-2006}/F_{MSY}$ and $SB_{2004-2006}/SB_{MSY}$ are highly variable between model configurations. In all credible model configurations, $F_{2004-2006}$ is estimated to be below F_{MSY}, $B_{2004-2006}$ is estimated to be above B_{MSY}, and $SB_{2004-2006}$ is estimated to be above SB_{MSY}. There is no indication that current levels of catch are not sustainable.

Given the uncertainty in the results, the evident sources of potential bias, and the less optimistic implications of the results than in previous assessments, further efforts to improve the model should be considered a high priority. A number of potential research directions are suggested.

2   Introduction

This paper presents the current stock assessment of albacore tuna (*Thunnus alalunga*) in the south Pacific Ocean. 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 ($B_{2004-2006} / \tilde{B}_{MSY}$) and recent fishing mortality to the fishing mortality at MSY ($F_{2004-2006} / \tilde{F}_{MSY}$). The methodology used for the assessment is that commonly known as MULTIFAN-CL (Fournier *et al.* 1998, Hampton and Fournier 2001, Kleiber *et al.* 2006, 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.

3   Background

3.1   Biology

Albacore tuna comprise a discrete stock in the South Pacific Ocean (Murray 1994). Mature albacore (above a minimum length of about 80 cm FL) spawn in tropical and sub-tropical waters between about 10°S and 25°S during the austral summer (Ramon and Bailey 1996), with juveniles recruiting to surface fisheries in New Zealand coastal waters and in the vicinity of the sub-tropical convergence zone (STCZ − about 40°S) in the central Pacific about 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 migrate seasonally 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 migration of albacore south during early summer and north during winter. This movement tends to correspond with the seasonal oscillation of the location of the 23−28° C isotherm of sea surface temperature.

Daily otolith growth increments indicate that initial growth is rapid, achieving a length of 45−50 cm (F.L.) in the first year (Leroy and Lehodey 2004). Subsequent growth is slower, at approximately 10 cm per year from age 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 0.2–0.5 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.

3.2   Fisheries

Distant-water longline fleets of Japan, Korea and Chinese Taipei, 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 has expanded considerably with the development or expansion of small-scale longline fisheries in several Pacific Island countries, notably Samoa, American Samoa, Fiji, Tonga, Cook Islands, New Caledonia and French Polynesia. A troll fishery for juvenile albacore has 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 Chinese Taipei 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 are now about 60,000 to 70,000 mt (Figure 4). Longline gear accounts for most of the catch, about 25-30,000 mt per year on average prior to about 1998. The increase in longline catch to approximately 70,000 mt in 2005 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.

4   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.

4.1   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 (Hampton 2002, Hampton and Fournier 2001, Labelle and Hampton 2003). This stratification was defined to account for the distinctive size segregation by latitude, with the smallest fish being found in southern waters.

For the 2005 assessment (Langley and Hampton 2005), the stock assessment area was divided into four separate strata delineated by latitude 30°S and longitude 180°, based on 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. Consideration was also given to areas of operation of the main domestic longline fisheries, to simplify the application of assessment results to the local scale management of these fisheries.

For the current assessment, two changes have been made to spatial stratification. First, the latitudinal boundary at 30°S has been moved north to 25°S, after examination of length frequency data (Langley and Hoyle 2008). Average length of fish frequencies between 25° and 30° tend to be smaller than those further north, and more similar to the southern strata than the northern strata. The model assumes the same selectivity throughout a fishery, so consistency in catch size compositions within time-area strata is desirable. The effect of this change was examined in a sensitivity analysis.

Second, two additional strata were added to the east of the previous boundary at 110°W. Catch from these strata (mainly from Japanese distant water longline fisheries) has previously been included in the model, but the length frequency data have not been. Adding the additional strata allowed these length frequency data to be included. The effect of this change was examined in a sensitivity analysis.

These strata were used to define the individual fisheries (see Section 4.3). As in the two previous assessments, uncertainties regarding the parameterisation of movement of albacore between the regions warranted adopting a single model region , with the six spatial strata being used to define fisheries.

4.2   Temporal stratification

The time period covered by the assessment is 1952–2007. Within this period, data were compiled into quarters (Jan–Mar, Apr–Jun, Jul–Sep, Oct–Dec). Data from 2007 are very limited and for most purposes inferences should focus on results to 2006.

4.3   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.

Several changes were made from the structure used in the 2006 assessment. First, the composite Japan/Korea fisheries were separated by flag. GLM analyses indicate temporal trends in catch per unit effort that differ between these flags in each region, (Bigelow and Hoyle 2008), as did length frequency distributions (Langley and Hoyle 2008). Second, two composite longline fisheries were added in the new eastern regions. Catch and effort in these regions is mainly Japanese. Third, a composite fishery for region 3 was added, because moving the latitudinal boundary north by 5 degrees included appreciable catch and effort in this region. The effects of the first and second changes were examined using sensitivity analysis. We considered the third change to be relatively minor and did not examine it further.

In summary, a total of 30 fisheries were initially defined for the assessment, including 26 separate longline fisheries, two driftnet fisheries, and two troll fisheries (Table **1**). The longline fisheries were comprised of Japanese, Korean and Chinese Taipei longline fisheries in each of the four western and central regions (12), 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 fisheries for the remaining longline data from all six regions (6). Separate troll and driftnet fisheries were defined for the south-western and south central regions of the assessment area. The geographic distribution of the cumulative catch from each fishery is presented in Figure 6.

Working from this initial structure, further changes were made to fisheries within the model. These changes may be thought of as technical changes to the way selectivity and catchability are modelled. However, since they were implemented via the definition of fisheries, they are mentioned here for the sake of completeness. First, seasonality in selectivity was modelled by

splitting each longline fishery into 4, by quarter. Second, temporal changes in selectivity were examined by splitting fisheries into discrete time periods.

4.4   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 catch (fisheries 1, 8, 15, 21, 29, 30). Catch and effort data have been provided by the National Research Institute of Far Seas Fisheries (NRIFSF) at 5 degree square, month resolution for 1952–2006. 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 catch (fisheries 2, 9, 16, 22). Aggregated catch and effort data for Korean longliners have been provided 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 1975–2006, catch in numbers and effort at 5 degree square, month resolution have been provided. 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 spatial distribution of catch to 5 degree square, month resolution. These samples were also used to estimate catch in number from catch in weight. The aggregated data provided for the Korean distant-water longline fleet do not cover 100% of fishing activities (i.e. catch and effort). Therefore, the Korean distant-water longline data have been raised according to the proportion of total Korean longline catch of target tuna species (as provided in the latest version of the WCPFC TUNA FISHERY YEARBOOK), to the total Korean longline catch of target tuna species for the aggregated data provided by NFRDI for the WCPFC Convention Area. Coverage by area has not been taken into account when raising these data, that is, the annual coverage rate for the entire WCPO has been used to raise the data. Note that data for 1975 cover less than 10% of the total estimated catch and hence have not been raised. Catches in numbers were estimated from average weights derived from available size composition samples where catch in weight has not been provided.

Chinese Taipei longline catch (fisheries 3, 10, 17, 23). Catch in number and effort data for the Chinese Taipei distant-water longline fleet at 5 degree square, month resolution have been provided by the Overseas Fisheries Development Council of the Republic of China (OFDC) through the Council of Agriculture (1967–2006). The 1967-1993 data were corrected for landings by the OFP, following the method in Lawson (1997), while the 1994-1996 data were corrected for landings by OFDC. Data for 2002, 2004-2006 cover the WCPFC Convention Area while the other years cover the south Pacific Ocean. 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. Effort (in hundreds of hooks) has

been estimated for these years from Japanese longline CPUE data determined for broad areas of the Pacific Ocean in each year. These samples have also been used to estimate catch in number from catch in weight.

Japanese, Korean, and Chinese Taipei effort (1–3, 8-10, 15-17, and 21-23). For the distant water longline fisheries, effective (or standardised) effort was calculated by dividing catch by estimates of standardised catch-per-unit-effort (CPUE). The CPUE indices were obtained from generalized linear modelling (GLM) (Bigelow and Hoyle 2008) of data from the port sampling program at the Pago-Pago albacore cannery. Effort for quarters without CPUE estimates was defined as "missing". Time-series of CPUE for all fisheries are shown in Figure 8.

Since vessels offloading at the albacore canneries have predominantly targeted albacore, the population model relies heavily on the CPUE trends derived from these fisheries.

Domestic longline fleets (fisheries 4-7, 11-14, 18-20, 24). 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, with 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, from domestic fleets operating outside their main region and smaller domestic longline fleets (e.g. Cook Islands, Vanuatu, Papua New Guinea, Solomon Islands) were compiled into separate fisheries in regions 1 to 4. Catch and effort reported in regions 5 and 6 were added to the data from distant water longline fisheries in those regions.

NZ domestic troll (fishery 25). Estimates of catch in weight and effort by 5 degree square and month for the period 1982–1992 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. Operational catch and effort data for the period 1993-2006 have been aggregated and raised according to annual catch estimates.

Effective (or standardised) effort was calculated by dividing catch by estimates of standardised catch-per-unit-effort (CPUE). The standardised CPUE indices were obtained from generalized linear and generalised additive modelling (GLM, GAM) (Unwin *et al.* 2005) of data from the New Zealand domestic fishery. Effort for quarters without CPUE estimates was defined as "missing". Time-series of CPUE for all fisheries are shown in Figure 8.

STCZ troll (fishery 26). 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 1986−2007. Likewise, data for New Zealand vessels has been provided at the same resolution. Where catch in number are not available, catches in numbers have been determined from average weights estimated from size composition samples.

Driftnet (fisheries 27-28). Catch in weight 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 Chinese Taipei fleet have been provided by the National Taiwan University. As there is some difference in effort units used by the Japanese and Chinese Taipei fleets, we have standardized Chinese Taipei driftnet effort to equivalent Japanese units by dividing the Chinese Taipei 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.

4.4.1   CPUE

The standardized CPUE data are generally consistent across seasons, regions, and fleets, although with some variation (Figure 8). A notable trend is the early decline for Japan, Korea, and Chinese Taipei (the distant water longline fishing nations or DWFN's) in all regions. For these fleets, catch rates were relatively stable from the mid-1970's until the 1990's. The Korean fleet in region 2 experienced a peak of standardized CPUE in the mid-1990's, as did the Chinese Taipei fleet in region 1 and 2 in the early 2000s. These peaks may be artefacts of the standardization process. Standardized CPUE data after 2000 are only available for the Chinese Taipei fisheries, all of which show a steep decline, which starts in about 1995 in the southern fleets.

Unstandardized CPUE data show a variety of trends by fishery. In region 1, Australian longline CPUE increased sharply in 2006, coincident with a switch in targeting towards albacore. Fijian CPUE increased rapidly during the 1990's before becoming more variable. In region 2, catch rates for the pooled Samoan fleets have declined a great deal since the early 1990's , though this pooled fishery represents a changing mixture of vessels with different catch rates. The Tongan fishery also shows a steep decline from the late 1980's until the present. Catch rates of the French Polynesian fleet increased from the early to late 1990's, and have declined steeply since then. In region 3, the Australian longline CPUE during seasons 2 and 3 has been increasing since 2005, coincident with a change in targeting towards albacore. The New Zealand longline fishery CPUE has declined since the late 1990's, associated with a switch in targeting towards swordfish. The 'other' fisheries are a shifting mixture of fleets with differing catch rates, and will be disregarded.

4.5   Length-frequency data

Available length-frequency data for each of the defined fisheries were compiled into 100 1-cm size classes (30−129 cm). Each length-frequency observation consisted of the actual number of albacore measured. The data were collected in respect of sources as follows:

Japanese, Korean and Chinese Taipei 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 Chinese Taipei 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.

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 and compiled through the Albacore Research Tagging Project (1991-1992) and by port sampling programmes in Levuka (Fiji), Pago Pago (American Samoa) and Papeete (French Polynesia), and, during the 1990−1991 and 1991−1992 seasons, 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 Chinese Taipei vessels also.

For each fishery, the temporal coverage of length frequency sampling is presented in Figure 10. No length samples were available from fisheries 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. For the long-standing Japanese and Korean longline fisheries and the Chinese Taipei longline fisheries, length samples are available from the early 1960s onwards. However, as discussed later, length frequency data collected in Pago Pago before 1971 were not included in the base case of this assessment (see also Hoyle *et al.* 2008), leaving only samples from the Japanese longline fisheries from 1962 to 1970 (Figure 10).

For the northern regions (1 and 2), the catches were principally comprised of large albacore (80–110 cm FL), while until recent years, smaller fish have comprised a high proportion of the catch from the southern regions (regions 3 and 4). For each of the main fisheries, there was a general increase in the length of fish in the catch from the 1960s to the present (**Figure 11**).

4.6   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 12). 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 13). 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 13). The Chinese Taipei 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 12).

4.7   Biological parameters

The biological parameters included in the model are presented in Table 2. These have been re-calculated since the 2006 assessment, based on new analyses of biological data (Hoyle 2008). The length-weight relationship is estimated from available length-weight data (Hampton 2002), with an alternative from Australian data (Farley and Clear 2008) trialled in a sensitivity analysis. The von Bertalanffy growth parameters are provided as initial starting values in the model. Variation in natural mortality with age is assumed (**Figure 9**), at values estimated from sex ratio at length

data (Hoyle 2008). A mean value of 0.4 is assumed for natural mortality, with alternative values trialled in sensitivity analyses. M was estimated in previous assessments, and in initial runs for this assessment, but in later runs the estimates were rejected as unrealistic.

5   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 (but make necessary assumptions for model processes), and on the other, to allow sufficient flexibility 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.

5.1   Observation models for the data

Three data components 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. To obtain the effective sample size, the minimum of the observed sample size and 1000 is obtained, and then multiplied by the effective sample size multiplier. The effective sample size multiplier recognises that length-frequency samples are neither truly random nor independent. This multiplier was 0.1 in previous assessments, but as one of the sensitivity analyses in this assessment, was changed to 0.05. The reasons for this are discussed in detail later in this document. This change is examined in a sensitivity analysis, as is a further reduction to 0.025. A further sensitivity analysis set the length frequency multiplier to 1 for the New Zealand troll fisheries, in order to constrain the model to fit these recruitment modes.

A log-likelihood component for the tag data was computed using a Poisson distribution, as in the 2005 and 2006 assessments. Previous analyses had assumed a negative binomial error structure, but the negative binomial distribution approximates the Poisson error structure as the overdispersion parameter tends to zero. Given previous low estimates of this parameter, it was not considered to be worthwhile estimating the additional parameter associated with the negative binomial.

5.2   Tag reporting

Tag-reporting rates are estimated with relatively uninformative Bayesian priors, as little independent information is available. There also appeared to be little information in the data to sustain the 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 and tag shedding.

Tag reporting rates were assumed to be equivalent across all four regions within each of the distant water longline fishing nations. The composite fisheries in regions 5 and 6 were assumed to have reporting rates equivalent to the Japanese longline fisheries.

5.3   Tag mixing

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

5.4   Recruitment

"Recruitment" in terms of the MULTIFAN-CL model is the appearance of age-class 1 fish in the population. Juvenile albacore tend to be caught mainly in the cooler temperate waters of the south Pacific, where reproductive activity is also distributed (Ramon and Bailey 1996). In the single region model currently used, 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). 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. In the current assessment, the "steepness" coefficient (S) of the SRR was fixed at 0.90, 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 *et al.* 2003). 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%). Sensitivity analyses were carried out to alternative steepness values of 0.95 and 0.75.

5.5   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.

5.6   Selectivity

Selectivity is fishery-specific and assumed to be time-invariant, and length-based to the extent that ages with similar lengths must have similar selectivities at age. 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. The estimated selectivities at age have a range of 0–1. All selectivities were constrained such that the selectivity of the last two age classes was equivalent.

Compared to the 2006 assessment, the length frequency data were more complete among fisheries. This enabled selectivity to be estimated for each longline fishery, unlike the previous assessment in which the Australian and New Caledonia longline fisheries in region 1 and Australian and New Zealand longline fisheries in region 3 shared common selectivities. A single selectivity was assumed for the drift-net fisheries in regions 3 and 4.

Selectivity is a highly influential component of the model. It affects the size distribution of the fish removed from the population, but its influence on the expected length frequency distribution is more important, given the relative importance of length frequency data in the total likelihood function. Previous assessments have highlighted conflicts between information in the length frequency and the CPUE data (Langley and Hampton 2005, Langley and Hampton 2006). Based on analysis of length frequency data (Langley and Hoyle 2008), considerable work was undertaken to improve the way selectivity was modelled.

Two main changes were made compared to the 2006 assessment. First, all longline fisheries were split into four by quarter. This change was made to accommodate strong seasonal variation in the length of fish caught (Langley and Hoyle 2008), noted in all regions. A sensitivity analysis was carried out for this change.

Second, selectivity was permitted to peak and then decline at larger sizes for most longline fisheries. Although longline fisheries catch mainly adult albacore, southern fisheries catch many more small fish than do those to the north. There is also considerable variation seasonally and among fleets and regions in the maximum size of fish caught. These differences reflect spatio-temporal variation in fish distribution at size, as well as the fishing practices of the fleets. Although the single region model assumes a single well-mixed pool of fish, selectivity can be used to adjust for variation in expected size distribution among fisheries. Only the three fisheries in which the largest fish were observed were constrained to have non-declining selectivity. These were the Australian region 1 longline fishery in quarters 3 and 4, and the Korean region 2 longline fishery in quarter 2. A sensitivity analysis was carried out to examine the effect of this change.

The selectivity functions for the troll and drift net fisheries, which principally catch juvenile albacore, were not divided seasonally.

5.6.1   Time varying selectivity

Changing selectivity through time has been suggested as a reason for increasing mean length of fish observed in longline fisheries (Langley and Hampton 2005, Langley and Hampton 2006). Multifan-CL does not have the facility to vary selectivity through time within a fishery; selectivity is constrained to be constant. As a sensitivity analysis, we used an alternative approach of splitting each of the seasonal and regional Japanese, Korean and Chinese Taipei longline fisheries into period-specific fisheries, and estimating selectivity and catchability (which is confounded with selectivity) separately for each fishery-period. In order to retain the long-term index of abundance over the periods, the splits by fishery were offset from one another in time. The divided fisheries shared tag return rates and length frequency sample size weighting. In the

first two options below, the length frequency data from southern fisheries were down-weighted with length-frequency multiplier of 0.05, in order to reduce the influence of the non-split data. In the third option, the lower southern LF weight was retained, to enable comparison of likelihoods.

Three options were trialled:

1. One northern split: the Chinese Taipei and Japanese fisheries were each split into two periods, pre- and post-1990 in region 1, and pre- and post-1986 in region 2. The Korean fisheries were split in 1986 in region 1 and 1990 in region 2. There were no splits in regions 3 and 4.

2. Three northern splits: Chinese Taipei, Japanese, and Korean fisheries were each split into four periods, at 1970, 1985, and 2000 in regions 1 and 2. There were no splits in regions 3 and 4.

3. Two splits, north and south: Fisheries in regions 1 and 4 were each split into three periods, at 1971 and 1990, while fisheries in regions 2 and 3 were split at 1975 and 1986.

5.7   Catchability

Catchability was assumed to be constant over time for all distant water longline fisheries (Japanese, Korean, and Chinese Taipei fleets). This assumption was based on the fact that catch per unit effort for these fisheries was derived from standardisation of data from vessels offloading albacore at the Pago-Pago canneries (Bigelow and Hoyle 2008). Similarly, catchability was assumed to be constant for the troll fishery in region 3, since the catch rate was based on standardization of New Zealand CPUE data (Unwin et al. 2005).

Catchability for all other fisheries was allowed to vary over time (akin to a random walk) using a structural time-series approach. Changes were made from the approach in the 2006 assessment, in order to free up the movement of the catchability deviates, and so reduce the potential influence of unstandardized CPUE on the assessment. Random walk steps were taken twice yearly (or annually in seasonal versions of the model) rather than biennially; and deviations were constrained by a prior distribution of mean zero and a variance equivalent to a CV of 0.7 (rather than 0.1) on a log scale. The influence of this change was examined with a sensitivity analysis.

Seasonal variation in catchability – independently estimated for each fishery – was allowed to explain the strong seasonal variability in CPUE for fisheries that had not been split seasonally.

Effort creep may occur when technological improvements, such as remote sensing equipment, GPS, better communication equipment, and/or higher vessel speeds, allow vessels to improve their ability to find and catch fish. As a sensitivity analysis, we modelled effort creep by increasing catchability of all fisheries by 0.5% per year. This change would primarily affect the fisheries with standardized CPUE, and not those fisheries in which temporal catchability deviates are estimated.

5.8   Effort variability

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

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

5.9   Natural mortality

Mean natural mortality was fixed at an initial value of 0.4, with variation at age as estimated from analysis of sex ratio at length data. The increasing skew in the sex ratio towards males is hypothesised to be due to higher natural mortality of sexually mature females than for males of the same age or size (although other possible explanations should be considered) (Harley and Maunder 2003). This increase in female natural mortality is modelled, and their subsequent loss from the population, is implemented in the single sex model via an increase at the age of female sexual maturity, and subsequent decline towards the constant male value.

Fishery data are usually uninformative about natural mortality, and attempts to estimate the mean value in this case resulted in unrealistic values greater than 0.9.

5.10   Initial population

The population was assumed to be at equilibrium in the first year of the model (1960) and the initial age structure is determined as a function of the estimated value of natural mortality and an initial fishing pressure being the average for the first three years of the assessment period. Using the average for between two and five years was compared, and both two and three years gave similarly good fits to the observed data, based on the likelihood. Using either two or three years was also consistent with the observed trend in fishing pressure, given low reported catches during the 1950's, and the increase in fishing pressure in the fourth and fifth years.

The 2005 and 2006 assessments assumed an initial year of 1952, although there is a lack of standardized CPUE or length frequency data before 1960. These assessments experienced difficulty starting in 1960 with an average of 5 years fishing mortality, due to very high initial exploitation rates on the age classes vulnerable to the longline fishery. However, probably due to changes in the input CPUE and length frequency data, the current assessment did not experience this problem. A sensitivity analysis was carried out to explore the effects of this change.

5.11   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.

5.12   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 (2006). 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).

5.12.1   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 $B0_t$ incorporate recruitment variability, their ratio at each time step of the analysis $\dfrac{B_t}{B_{0t}}$ can be interpreted as an index of fishery depletion.

5.12.2   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 0.01, 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.

5.13   Alternative structural scenarios

A set of alternative structural scenarios was run in order to examine the effects of structural uncertainty. These runs were carried out before the problem with the effort deviates was resolved, so should be used mainly to indicate the degree of structural uncertainty in the model, and to compare among the components.

A grid was run across all possible combinations of the following scenarios:

1.   Steepness parameter of 0.75, or 0.95;
2.   growth curve estimated, or fixed at the Australian growth curve;
3.   no effort creep, or 0.5% effort creep per annum;
4.   mean natural mortality of 0.4 or 0.45;
5.   no time split, or time split as in scenario 3 (see Section 5.6.1);
6.   effective sample size for length frequency data as in the base case, or down-weighted by a further 50%;
7.   model start year of 1960, or 1971.

5.14   Summary of changes since last assessment

The main changes to the base case since the 2006 assessment were:
1.   Update biological parameters (natural mortality and 'maturity' parameters).
2.   Two spatial strata added to the east (one fishery each in annual model).
3.   Boundary moved from 30S to 25S.
4.   Separate Japanese and Korean fisheries.

5. Include standardized CPUE from Pago-Pago in Japanese, Korean, and Chinese Taipei fisheries, without catchability deviates.
6. Include standardized NZ troll CPUE and catch data as a fishery without catchability deviates.
7. Given inconsistency of the LF data, reducing the effective sample size multiplier from 0.1 to 0.05.
8. Make longline fisheries seasonal.
9. Remove Pago LF data before 1971.
10. Reduce the influence of CPUE from non-standardized fisheries by estimating q deviates at 11 months for seasonal models, and 5 months for others.
11. Allow selectivity to decline for longline fisheries, except for those that catch the largest fish.

Some of the above changes were recommended at a preparatory meeting held in February at the Secretariat of the Pacific Community, Noumea (Langley and Hoyle 2008). A list of these recommendations and our responses is given in Table 4.

6   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 results. These sensitivity analyses include the changes described above in section 5.14, which were included in the base case, as well as other changes described in the Methods section. This section summarises the results of these sensitivity analyses. From these results, a preferred assessment was chosen as the "base case", and the results of this model are presented in detail. Yield estimates and performance indicators are derived for the base case assessment, along with complementary results from a sensitivity analysis that is less affected by the steep decline in Chinese Taipei CPUE at the end of the time series.

6.1   Structural changes

The primary aim of many of the changes referred to above (Section 5.14) was to reduce the data conflict that has affected previous south Pacific albacore stock assessments. The declining CPUE observed in the Chinese Taipei catch-effort series has not been matched by the expected smaller sizes (given increasing catches) in the length frequency data (Langley & Hampton 2005). As a result, the model has estimated long-term trends in recruitment in order to resolve the data conflict.

We also note that although changes in the total likelihood can in some circumstances be used to compare the overall goodness of model fit, this is in the context of the fit of the model over all data types. If there is substantial mis-specification of the model (due to, for example, unresolved data or structural problems), then relative goodness of fit in terms of the total likelihood function can be misleading.

The various model options for varying the structural assumptions were examined with respect to the trends in model estimates of adult biomass and annual recruitments (Figure 14 to Figure 17) and described below. The structural changes were made to the model in a mostly stepwise manner, so as to demonstrate the cumulative effect on the model towards the base case option. The number of estimated parameters, the -log likelihood values, and the relative biomass depletions levels are reported in Table 5. Where the number of fisheries or the amount of data changes, the likelihood changes cannot be used to compare goodness of fit. In some cases this is

because the effective sample size for length frequency data in MFCL has an upper limit, so changing the data configuration can change effective sample size, and hence the likelihood, irrespective of the goodness of fit.

6.1.1   Changes to data inputs

6.1.1.1   Add east separate JP, KR

Separating out the two new regions to the east, and separating the data from the Japanese and Korean fisheries, did not have a major effect on the overall biomass trends (Figure 14).

6.1.1.2   25 degree boundary

Moving the boundary north by 5 degrees however, resulted in more recruitment at the beginning of the time series and significantly changed the overall biomass trend. These model runs did not include the standardized CPUE data (which is added at a later step, below) and used mainly the Chinese Taipei CPUE, which shows a consistent decline over the period. The biomass trend changed because the conflict between CPUE and length frequency data had been reduced.

6.1.1.3   Start in 1960

Starting the model in 1960 changed the biomass trend between 1960 and 1965, partly because the initial equilibrium age structure tended to impose constant biomass for several years (**Figure 15**).

6.1.1.4   Clean catch data

Cleaning the catch data involved replacing catches in the aggregate annual catch weight data with instances of higher catches recorded in the operational data from Pago-Pago. This change had a minor effect on trends in model biomass.

6.1.1.5   Add LL GLM

Adding the standardised longline CPUE changed the overall biomass trend, with the greater likelihood penalty from fitting the model to more CPUE data over at least part of the time series. The likelihood deteriorated, given this increased penalty and more conflict between length frequency and CPUE data. The number of estimated parameters was reduced, given the removal of catchability deviates from the standardized fisheries.

6.1.1.6   Clean early LF data

Removing the Pago Pago length frequency data before 1971 had a very strong effect on the recruitments and the overall biomass trend. These data were clearly influential, as was observed when examining the 2006 assessment (Hoyle *et al.* 2008). The initial biomass increased relative to later biomasses, with the early trend following the CPUE data more closely. The very high initial recruitment and subsequent variability may be partly due to problems with initial equilibrium, which are addressed later. The timing of recruitment also changed, due to a large change in the growth rate. Removing these early LF data resulted in the estimated growth rate parameter k changing from 0.23 y^{-1} to 0.33 y^{-1}, with only a slight change in Lmax, from 99.7 cm to 100.5 cm. At the same time, natural mortality (which was estimated in these initial model runs) increased (unrealistically) from 0.45 to 0.63. These changes reflect the interdependence of growth, selectivity, and total mortality, and the importance of length frequency data for estimating them. When there is strong lack of fit, the model may fail to track growth modes, and instead try to proxy for other features of the data using indirectly related parameters.

The apparent deterioration in the likelihood is due to removal of data from particular strata, so that the constant terms associated with the likelihoods of those data no longer contribute to the likelihood.

6.1.2   Changes to model parameterization

6.1.2.1   *Loosen early q deviates*

Loosening the catchability deviates removed the influence of the non-standardized CPUE time series. The main effect was to increase the biomass decline at the end of the time series, which is largely due to the lower standardized catch rates in the Chinese Taipei fisheries. It is uncertain whether this decline in standardized catch rates reflects mainly a decline in abundance, or is affected by a change in targeting (Bigelow and Hoyle 2008). Relaxing the catchability deviates resulted in an improved likelihood by 1125 units, with 541 more parameters being estimated.

6.1.2.2   *Sel can decline with age*

Allowing selectivity at age to decline (i.e. domed functions) for all longline fisheries except those in region 2 scaled down the entire biomass time series, partly because estimated natural mortality declined along with an increase in growth rate k. A declining selectivity function allows the model to account for some fisheries failing to catch large fish via reduced selectivity, rather than through the impacts of fishing or natural mortality on the population state, and produces an improvement in the quality of fit to catch at size data. However, the improvement in fit was surprisingly small at only 67 units, perhaps because seasonal selectivities were not added at this stage.

6.1.2.3   *Seasonal fisheries*

Introducing seasonality to selectivity improved the fit of the model by 2100 units, at the cost of 1042 parameters. Selectivity varied strongly by season, as expected given the seasonal effects observed in GLM analyses of albacore length frequency data (Langley and Hoyle 2008). Inter-annual recruitment variability became more apparent (Figure 16). The reduced uncertainty in recruitment estimates (Figure 32) compared with previous assessments (Langley and Hampton 2005) may be due to this change. However, natural mortality also increased from 0.54 to 0.99. Being implausible, it was necessary to assume a fixed value for M in subsequent model options. Natural mortality is always a difficult parameter to estimate in fisheries models. It is confounded with many other parameters in the model, and has significant influence on stock assessment outcomes.

6.1.2.4   *Sel=1 in 3 fisheries, fix M*

The next model option allowed selectivity in the seasonal model to be non-declining in all but the three fisheries with characteristically broad catch at size distributions, and natural mortality was fixed at 0.4. This resulted in a substantially lower overall biomass estimate. Recruitment estimates were generally similar to those from the previous model option (seasonal selectivities). The fit to the data was slightly worse than the previous seasonal model, by 176.6 units, with almost all of this change (175.5) due to fixing natural mortality. The two options for selectivity parameterisation were deemed equivalent, and the second option was retained since it seemed more consistent with our view of the fisheries. This model option was used as the **reference case** for further sensitivity analyses, as a stepping stone towards the base case.

At this point, we note that all the recruitment series show a declining trend, from the 1960's to the present day. As in previous assessments, the model is using recruitment trends to explain long-term declines in catch rate that are not matched by the expected smaller sizes (given increasing catches) in the length frequency data. Removing the early Pago Pago length frequency data

resolved some of the conflict between the information in the two types, but some conflict remains.

6.1.3   Sensitivity analyses

As recommended by the stock assessment preparatory meeting (Langley and Hoyle 2008), a number of sensitivity analyses were carried out: to the length weight relationship; to the growth curve; and to including the standardized New Zealand troll data effort series.

6.1.3.1   Length-weight relationship

Using an alternative length-weight relationship had (as expected) no effect on recruitment estimates and a small effect on overall biomass. Since most of the data are provided in numbers rather than in weight, there is little effect on trends in numbers or on stock status indicators.

6.1.3.2   Australian growth curve

Assuming the Australian growth curve (Farley and Clear 2008) rather than estimating growth rate produced a significant change, since it altered the estimated ages of fish observed at length, and therefore changed the timing of recruitment pulses (Figure 17). With the structural changes described above, the model tended to estimate a growth curve (option 'Sel in 3 fisheries, fix M', k = 0.37, Lmax = 100.3) more similar to the Australian growth curve (k = 0.32, Lmax = 102.9), than to the value estimated in previous assessments, such as that from the 2006 assessment (k = 0.21, Lmax = 105, Langley and Hampton 2006). The model fit deteriorated by 37 likelihood units with the Australian growth curve.

6.1.3.3   NZ troll GLM

Including the standardized New Zealand troll effort series (Unwin *et al.* 2005) had a considerable effect on biomass and recruitment trends. By providing information between 1993 and 2004, the effect was to counteract the declining trend in estimated recruitment, and so "flatten" the recruitment series. Since this declining recruitment was being used by the model to explain the increasing sizes of fish caught in the longline fisheries, it is unsurprising that adding the New Zealand troll data worsened overall model fit by 693 likelihood units. However, standardized NZ troll data are only available from 1993 to 2004, so the recruitment trend was only flattened for this period. It would be useful to have a longer time series of standardized recruitment data.

6.1.4   Further sensitivity analyses

In addition to the changes requested by the preparatory meeting, further options were examined, with a view to removing more of the inconsistencies observed in the model diagnostics, and examining model sensitivity. More detail of these changes is given above, in the Methods section.

1. Steepness of 0.7 and 0.98
2. Include effort creep of 0.5% per year
3. Down-weight length frequency data with multiplier of 0.05
4. Up-weight NZ troll LF
5. Estimate length at age 1
6. Time-varying selectivity

6.1.4.1   Steepness=0.7, 0.98

Varying the assumed steepness had, as expected, little effect on population dynamics (**Figure 18**) but considerable impact on the MSY-related parameters (Table 5). Steepness of 0.7 reduced the F

multiplier (F_{MSY}/F) by approximately 50%, while steepness of 0.98 raised the F multiplier by about 55%.

6.1.4.2   Effort creep

Introducing 0.5% effort creep per year increased the rate of biomass decline as expected, since it implies that catch rates should be higher at the same biomass later in the time series. Adding effort creep appeared to increase the conflict between the CPUE data (suggesting biomass decline) and the length frequency data (increasing fish sizes). The likelihood deteriorated by 43.8 units. Unexpectedly, B/B_{MSY} remained similar (from 1.19 to 1.13). Fmult actually increased (from 5.37 to 5.72), most likely because of the combination of higher biomass at the same level of catch, and slightly higher productivity (k=0.374 versus 0.373).

6.1.4.3   Down-weight LF data

Changing the length frequency data multiplier from 0.1 to 0.05 ('Down-weight LF data') gave the CPUE data more influence relative to the length frequency data. This resulted in a steeper decline early in the time series, reflecting the observed CPUE trend. As in most cases when the influence of the increasing observed fish size was reduced, the overall time series was estimated to be lower, with more impact from fishing (Fmult = 4.36) and less of a declining trend in recruitments after 1970.

6.1.4.4   Up-wt NZ troll LF

Changing the NZ troll fishery effective sample size multiplier from 0.1 to 0.2 had little effect on the results. However, it appears appropriate to give this data series more weight than the other length frequency data, given that there do not appear to be problems with changing selectivity in this fishery. The increased weight did not help the model fit the clear recruitment modes from this fishery. On examining the fit more closely, the expected and observed length modes in the troll fisheries appeared to be offset. Only increasing the weight to 1 adjusted the mean length at age and achieved a good fit to juvenile recruitment nodes, but produced a worse fit to other length frequency data. The von Bertalanffy growth curve may not predict length at age for young fish closely enough for the model to track the growth of these cohorts. Alternative growth curves should be explored to help resolve this problem..

6.1.4.5   Estimate length at age 1

Estimating length at age 1 improved the likelihood by 40.5 units for one additional parameter. It resulted in changes to the timing of some recruitments, but had little effect on the biomass trend or management-related parameters.

6.1.4.6   Selectivity splits

Due to the observed increase in the size of fish caught by longliners over the model period, time variation was introduced into selectivity. Introducing time-variation into selectivity had very large effects on biomass, with flatter biomass trends after 1970 (**Figure 19**) and more impact from fishing. Option 1, with a single split in northern regions in either 1990 or 1986, had a steeper decline early in the time series with a flatter trend, and lower biomass after 1975.

Option 2 (3 time splits in the northern regions) and option 3 (2 offset time splits in north and south) produced lower biomass overall (**Figure 19** and **Figure 20**), higher impacts of fishing (Fmult =2 and Fmult=1.37), and quite different growth curves (k=0.245 and k=0.312), resulting in offset recruitments (**Figure 19**). There was a significant improvement in the shape of the recruitment distribution, with the anomalously high initial recruitment being replaced by more normally distributed recruitment series.

Each additional time split improved the fit of the model to the data, although option 1 cannot be compared with the reference model option in terms of total likelihood, because of the down-weighted length frequency data. The option with three time splits for the northern fisheries improved the likelihood by 546 at the cost of 362 parameters. Two time splits in both north and south improved the likelihood by another 960 units, with 11 fewer parameters estimated.

Note, however, that this 'selectivity split' technique is intended only as a sensitivity analysis, to determine how ignoring the process of changing selectivity may be affecting the stock assessment. It would be premature to use it as a basis for assessing stock status. The offsets did not successfully 'link up' the separated fisheries with their shared CPUE time series. The two latter split options estimated early 2000 biomass to be close to or above unfished levels, despite much lower CPUE at present. In addition, the timing of the selectivity splits was chosen arbitrarily, rather than by observing the timing of length changes, and we currently have little basis for choosing among the selectivity-split options presented. Selectivity changes are likely to occur as a trend rather than in jumps, and an approach that takes this into account is likely to be more successful. For example, it may be possible to use hooks between floats as an indicator of gear configuration, and use it to as a covariate in the model.

6.1.5   Final configurations

A final configuration was chosen on the basis of the sensitivity analyses. The following changes were made from the reference case.

     a. Estimate length at age 1 year
     b. Down-weight length frequency data with multiplier of 0.05, except for NZ troll data
     c. Include standardized New Zealand troll data

This final configuration produced lower biomass estimates overall compared to the reference model option, a similar B/B_{MSY} ratio (1.18), and a lower Fmult (2.51).

6.1.5.1   Final + repair effort deviates

However, at this point a problem became apparent with the estimated effort deviates. Effort in standardized fisheries had been set to -1 for all periods in which standardized CPUE estimates were not available. Effort deviates for these periods should not be included in the likelihood, but appeared to be affecting the other effort deviates in some fisheries, and therefore the likelihood. The problem was repaired for all effort series in which this problem was observed (JP LL R1 seasons 3 and 4; JP LL R3 seasons 2-4; JP LL R4 seasons 1-4; KR LL R4 season 2) by moving data for all periods with missing effort into new fisheries, setting effort equal to catch, and sharing relevant parameters (e.g. selectivity, tag groups) with their parent fishery. With no time to rerun all previous analyses, only the final configuration was rerun. The resulting change to the time series indicated the need to be cautious when using -1 for missing effort. Changes to MFCL may be needed to avoid the need for the fishery splitting strategy.

6.1.5.2   Tighten q deviates

In a final sensitivity analysis, catchability (q) deviates were returned to the previous configuration, with deviates estimated every two years, with standard deviation of 0.1.

6.2   Fit diagnostics

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 (Figure 22) are relatively small, due to the large penalties that constrain observed catch to be well estimated. Trends are apparent in the residuals for all the standardized fisheries, with a declining trend in the earliest part of the time series for the standardized longline fleets, and a strong increasing trend for the standardized New Zealand troll fishery. These trends are partly due to the remaining conflict between length frequency and CPUE data, and also to CPUE trends from the different standardized fisheries being slightly different. There may also be a remaining problem with missing effort.

- The model predicts the number of tag recoveries from the population at each time interval (Figure 23). 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 23). 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 over the following decade as tags are lost from the population.

- The observed and predicted recoveries can also be compared with respect to the period at liberty of the tagged fish (Figure 24). The model predicts fewer returns than observed with increased time at liberty, largely due to the cumulative effects of natural and fishing mortality. The model fit to the tagging data for this version of the model considerably better than earlier versions that had higher biomass and lower fishing mortality. However, the model still tends to underestimate tag returns for fish at liberty for between 6 and 20 months, and to over-estimate returns, on average, after this (Figure 24). The rate of decline of expected returns is lower than observed, which may suggest that the tagging data indicate higher total mortality than the overall model estimate. Several other factors may also contribute to the observed decline however, such as slower mixing than expected out of the tagging area in which a number of the early fish were caught, progressive tag shedding, and increased mortality of tagged fish.

- The tagging data are relatively uninformative in the model, largely due to the low numbers of tag returns and the model's freedom to estimate fishery specific reporting rates. 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 immediate 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 among all longline fisheries for each nationality.

- Overall, the highest estimated reporting rate was from the New Zealand longline fishery (49%); the Chinese Taipei longline fisheries had a relatively high reporting rate (12%) reflecting the numerous tags returned from these fisheries; and reporting rates for the Japanese and Korean longline fisheries were low (Figure 25). Return rates were high for

regional longline fisheries in region 3, where most tagging took place, and low elsewhere. This suggests that mixing was not complete within a short period, as was assumed in the model. This assumption is not reasonable in a model without spatial dynamics, and should be re-visited in future modelling work.

- For each fishery, the observed and predicted proportion of fish in each length class in the catch was compared for each sample (quarter) (**Figure 26**). For a number of the distant-water longline fisheries, and particularly in regions 2 and 4, there are strong temporal trends in the residuals. Many of these fisheries reveal a positive trend in the residuals i.e. the model under-estimates the proportion of small fish observed in the catch before about 1975, and over-estimates the number of fish observed after this time. This is expected given the increasing lengths observed in the length frequency data (Figure 10). There is also significant short-term variability among samples in some of the distant water longline fisheries, suggesting non-random sampling of the population. To deal with this it may be appropriate to further down-weight the length frequency data sample size.

- There also appear to be strong positive residual trends in the length frequency data in a few domestic longline fisheries, including the New Caledonian (**Figure 26**b) and New Zealand (**Figure 26**h) longline fisheries. These trends may represent changes in selectivity, since they appear to coincide with switches in targeting. It may be rewarding to determine the changes in gear configuration associated with these selectivity changes, and to split the fisheries according to frequency data.

- 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 27**), and in the plots of exploitable biomass versus observed CPUE (**Figure 28**). If the model is coherent with the effort data, we would expect an even scatter of effort deviations about zero. An obvious trend in the effort deviations with time may indicate either a trend in catchability that has not been sufficiently captured by the model, or a conflict with other information in the model. Such trends are evident in the effort deviations from most of the standardized fisheries, particularly during the later period of the fishery.

- Initial catch rates from these fisheries were high and declined sharply during the subsequent 10 years, particularly in regions 2 and 4 (see Figure 8). Catchability is assumed to be constant for these fisheries and the model has generally followed the biomass trend, but the CPUE decline is still a little steeper than the biomass decline, resulting in generally positive effort deviates early in the time series (**Figure 27**). The declining effort deviations during the 1960s and 1970s enabled the model to improve the fit to the observed catches during the period of rapid decline in catch rates from the fisheries. However, 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.

- High effort deviates late in the time series can be observed in the longline fisheries of Korea and Chinese Taipei in region 2. These occur due to large peaks in standardized CPUE. The peaks may represent problems with the CPUE analysis, and these high effort deviates will be affecting the modelled biomass trend.

- The Chinese Taipei longline fisheries in regions 3 and 4 decline late in the time series, indicating catch rates below those predicted, given the estimated biomass. The biomass trajectory is not declining as far as the Chinese Taipei CPUE is declining. Several factors may be contributing to this. First, size at full selectivity in the southern fisheries has increased, and the fishery now catches larger fish (which are less abundant) than are predicted by the model. This factor is likely to increase the decline of the CPUE trend. Second, given the increasing Chinese Taipei catches of swordfish and bigeye tuna, some Chinese Taipei

vessels in the albacore CPUE dataset may be targeting other species in addition to albacore, reducing their albacore catch rates.

- These systematic trends in the effort deviations are symptomatic of inconsistencies in the model population dynamics. 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 28**). The model underestimates the rate of decline in CPUE observed during the 1960s and early 1970s. It also estimates a decline in New Zealand troll fishery exploitable biomass between 1993 and 2004 that was not observed in the catch rates. The figure also illustrates the relatively high variation even in the standardized CPUE, data indicating the lack of precision associated with the catch and effort series - the principal index of stock abundance in the model.

- Peaks were observed in standardized catch rates in the Chinese Taipei fishery in region 1 and the Korean and Chinese Taipei fisheries in region 2 in the late 1990's (Figure 8). These are reflected in relatively high effort deviates, indicating that exploitable biomass has not fully tracked those peaks in CPUE.

6.3   Model parameter estimates

6.3.1   Catchability

Annual catchability for the standardized fisheries was held constant over the entire period of the model (Figure 29). Strong temporal trends in catchability are evident from other fisheries. Many of the domestic longline fisheries reveal an initial increase in catchability during the development of the fishery and a subsequent stabilization of catchability. An exception to this trend was the decline in catchability evident in the Samoa/American Samoa longline fisheries (Figure 29). In recent years, catchability has declined in the troll fishery operating in region 4. A number of fisheries show steep increases in catchability in the last few years. In some cases these reflect known changes in targeting (e.g. the Australian longline fishery in region 1), but others do not (e.g. Fiji, French Polynesia, New Caledonia, Samoa), suggesting that the recent biomass decline may be overestimated.

Catchability trends, and variation among seasons, also capture variability in availability for spatially restricted fisheries. Catchability in the northern fisheries tended to be high in seasons 3 and 4 and lower in seasons 1 and 2. In the southern regions 3 and 4, catchability was generally highest in seasons 2 and 3.

6.3.2   Selectivity

The selectivities for longline fisheries reveal some consistent seasonal patterns (**Figure 30**). However, the degree and pattern of variation among fleets and regions suggests that the estimates are affected by the combination of long term variation in selectivity, and temporal variation among fleets in the amount of effort and length frequency data.

Fisheries in the northern regions (1, 2, and 5) catch a higher proportion of older, adult albacore than most of those fisheries in the southern regions (3, 4, and 6). The troll and drift net fisheries, operating in the southern regions, principally exploit the 2–4 year age classes and the selectivity of the older age classes is very low.

The northern distant water longline fleets are estimated to catch younger fish than do the domestic fleets. This may be because their selectivity is assumed to be constant through time, and the distant water longline fleets have data from the 1960s and 70's, when smaller fish were caught. This illustrates the need for temporal variation in selectivity.

Of the northern distant water longline fleets, those in region 2 (the region with the most data) take larger fish in seasons 4 and 1, and smaller fish in season 2. Smaller fish are also taken in season 2 in regions 1 and 5, but the other seasons are more variable. The domestic fleets in northern regions also take smaller fish in season 2, with the largest fish generally being taken in season 3. Since seasons 2 and 3 are next to each other, it may be useful to examine the timing of the seasonal divisions and adjust them so they more accurately reflect (define) the timing of selectivity changes. There appears to be a parameter estimation problem for the Australian longline fleet in region 1, seasons 1 and 4.

In the southern regions, there is considerable selectivity variation among fleets and seasons. For the distant water longline fleets, this reflects the great changes in fish size distribution from the 1970s to the present day. To some extent it may also reflect un-modelled spatial variation, since domestic fisheries in the south and west (Australia and New Zealand fisheries in region 3) catch smaller fish than those further north and to the east ('Other' fisheries in region 3 and 4). The domestic fleets generally take smaller fish in seasons 2 and 3 (the main fishing season) than they do in seasons 1 and 4.

6.3.3   Growth

The estimated growth curve is shown in Figure 31. Growth rates are estimated to be higher than the established growth parameters used as starting values in the model, and higher than growth rates estimated in previous assessments. The estimates are close to the Australian growth curve estimate, with most difference occurring for young fish below about six years.

The estimated variability of length at age reduces with age, and is very low for the older age classes. This appears unrealistic and suggests a problem fitting to the length frequency data.

6.4   Stock assessment results

Results for the final configuration model with effort deviation corrections (base case model) are presented.

6.4.1   Recruitment

There is considerable temporal variation in recruitment over the model period (Figure 32), and the model is using this variation to drive the major biomass trends. The initial equilibrium recruitment is estimated to be well above mean recruitment. Subsequent annual recruitments are also estimated to have been high before 1965, stable but variable until the mid-1990's, and declining from that point through to the present.

The high initial recruitments may be consistent with the high proportion of small fish observed in the longline fisheries during the 1960s and 1970s (**Figure 11**), but also reflect the model's attempt to resolve conflicts among data sources. The high early recruitment estimates are also driven by the initial decline in CPUE observed from the distant water longline fisheries. The decline in recruitment since the mid-1990s represent the model's attempt to fit declines observed in distant water longline fisheries' CPUE during a period when fish size was not decreasing. The declining recruitment pattern is inconsistent with the standardized New Zealand troll fishery CPUE.

The recruitment estimates have comparatively tight confidence intervals indicating reasonable consistency among data sources about the short-term variability in recruitment, particularly during the period since the mid 1980's (Figure 32). The most recent recruitment estimates are very uncertain, reflecting fewer observations of recent year class strengths.

6.4.2   Biomass

Biomass was estimated to be high at the start of the 1960s due to the initial high equilibrium recruitment, decreasing during the 1960s mostly in response to average recruitment, declining at a slower rate through the 1970s until the mid-1990s, rising to a small peak in the late 1990's and subsequently declining dramatically, and perhaps unrealistically (Figure 33). The moderate level of parameter uncertainty associated with the annual biomass estimates progressively reduces through time. Structural uncertainty is more important. The recent decline is contingent on the recent Chinese Taipei CPUE being assumed to be informative.

The high initial recruitment results in biomass being initially well above the equilibrium unexploited biomass (B_0) (**Figure 34**), but after a period of average recruitment biomass declines to slightly below B_0. The recent estimated trend is a decline from slightly above B_0 to less than half of B_0.

6.4.3   Fishing mortality

Overall, fishing mortality (exploitation) rates for adult and, particularly, juvenile albacore are estimated to have gradually increased throughout the history of the fishery (Figure 35), with lower rate of increase from the early 1970s to 2000, and a large increase since that time, particularly for adult fish. For adult fish, exploitation rates increased during the initial development of the fisheries as catches rose and biomass declined. Estimated exploitation rates have increased since 2000 in response to higher catches (see Figure 4 and Figure 5) and lower levels of adult biomass imposed by the declining Chinese Taipei CPUE.

The fishing mortality rates for juvenile albacore peaked in 1989–90 corresponding to the peak period of drift net fishing (Figure 35), but in recent years have been estimated to be at a higher level, largely due to the decline in estimated recruitment.

Estimated fishing mortalities for the fully recruited age classes have reached very high levels in 2006, which may be implausible (**Figure 36**). By way of comparison, current annual fishing mortalities on adult bigeye tuna are estimated at approximately 0.5, with combined longline fishing mortality also peaking at about 0.5 on the 20 quarter age class.

6.4.4   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 the only impact of fishing on annual recruitment is through the stock recruitment relationship). 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. The estimated impact depends strongly on the selectivity of the fishery, so impacts differ for the different seasonal components of each longline fishery. The fishery impacts are consistent with the estimated fishing mortality rates.

The fishery impact on the component of the stock vulnerable to longline fisheries has increased over the last decade, with increasing catches and reduced biomass, and is estimated to be currently (2006) between about 30% and 70% i.e., longline-vulnerable biomass has been reduced by between 30% and 70% due to the impact of fishing (Table 9, Figure 37, Figure 38). The current level of impact on the component of the stock vulnerable to troll and driftnet fisheries is low (about 5 to 10%). The difference is due to the age-specific selectivity of the longline fisheries, which harvest fish in the oldest age classes. 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.

The relatively high impact on the longline exploitable biomass is particularly evident in the longline fisheries operating in the northern regions (regions 1, 2, and 5), while the impact on longline exploitable biomass in the southern regions (3, 4, and 6) is lower due to a higher proportion of younger fish in the catch (Figure 37). Impacts also vary seasonally, with more impact on seasons in which larger fish are taken (Figure 37 and Figure 38). 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 37).

Comparing the estimated impact of fishing on biomass (Figure 39) with the overall estimated biomass decline (Figure 40) demonstrates that the model is using recruitment to produce most of the initial estimated biomass decline, and a large part of the recent estimated biomass decline.

6.4.5   Yield analysis

Symbols used in the following discussion are defined in Table 8. The yield analyses conducted in this assessment incorporate the SRR (Figure 41) into the equilibrium biomass and yield computations. The estimated steepness coefficient of the SRR is 0.9, indicating a relatively weak relationship between stock and recruitment. Equilibrium yield and total biomass as functions of multiples of the 2004−2006 average fishing mortality-at-age (Fmult) are shown in Figure 42. Yield is maximized at Fmult = 2.3 for a MSY of 64,000 mt per annum. This implies that the ratio $F_{2004-2006}\big/\tilde{F}_{MSY}$ is approximately 0.44. The equilibrium biomass at MSY is estimated at 340,000 mt, approximately 49% of the equilibrium unexploited biomass. Equilibrium biomass is calculated under average recruitment, and biomass in 1960 was estimated to be more than twice B_0 because of the very high initial recruitment estimate.

6.4.6   Stock assessment conclusions

A number of quantities of potential management interest associated with the yield analyses are provided in Table 9. 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 $SB_{2004-2006}\big/S\tilde{B}_{MSY}$, $B_{2004-2006}\big/\tilde{B}_{MSY}$ and $F_{2004-2006}\big/\tilde{F}_{MSY}$ 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 ratios $B_{2004-2006}\big/B_{2004-2006,F=0}$ and $SB_{2004-2006}\big/SB_{2004-2006,F=0}$ can provide an indication of population depletion and fishing impact by the fisheries. Total biomass is estimated to be currently depleted by 30%, and spawning biomass by 50% (i.e., spawning biomass reduced by 50% due to the impact of fishing). This represents a moderate level of spawning biomass depletion, above the equivalent equilibrium-based limit reference points ($\tilde{B}_{MSY}\big/\tilde{B}_0 = 0.49$ and $SB_{MSY}\big/SB_0 = 0.18$). The equivalent depletion and impact parameters for the model with less flexible catchability deviates are more optimistic.

Other reference points useful in indicating the current status of the stock are $\tilde{Y}_{F_{2004-2006}}\!\big/MSY$ (0.86), $\tilde{B}_{F_{2004-2006}}\!\big/\tilde{B}_{MSY}$ (1.37) and $S\tilde{B}_{F_{2004-2006}}\!\big/S\tilde{B}_{MSY}$ (2.21). The yield-based reference point $\tilde{Y}_{F_{2004-2006}}\!\big/MSY$ suggests that the potential to expand long-term yields from the fishery at the current pattern of age-specific selectivity may be limited. The equivalent parameter for the model with less flexible catchability deviates ($\tilde{Y}_{F_{2004-2006}}\!\big/MSY = 0.72$) is slightly more optimistic. The total biomass-based reference point indicates that the long-term average biomass at current fishing mortality will be below that capable of producing MSY. The model with less flexible catchability deviates is again a little more positive ($\tilde{B}_{F_{2004-2006}}\!\big/\tilde{B}_{MSY} = 1.53$, $S\tilde{B}_{F_{2004-2006}}\!\big/S\tilde{B}_{MSY} = 2.90$).

The ratios $F_{2004-2006}\!\big/\tilde{F}_{MSY}$ (0.44), $SB_{2004-2006}\!\big/S\tilde{B}_{MSY}$ (2.99), and $B_{2004-2006}\!\big/\tilde{B}_{MSY}$ (1.26) do not indicate that overfishing of south Pacific albacore is occurring, nor is the stock in an overfished state. A profile likelihood distribution on the F multiplier ($\tilde{F}_{MSY}\!\big/F_{2004-2006}$) indicates that the 95% probability distribution does not include values below 1 where overfishing occurs (Figure 43). The biases and conflicts in the model structure, previously noted, suggest that these estimates are subject to considerable uncertainty. For the various structural alternatives investigated in this assessment, and considering the nature of possible biases involved, most other plausible stock assessment outcomes are more optimistic that those associated with the base case analysis, e.g. the equivalent values of $F_{2004-2006}\!\big/\tilde{F}_{MSY}$, $SB_{2004-2006}\!\big/S\tilde{B}_{MSY}$, and $B_{2004-2006}\!\big/\tilde{B}_{MSY}$ for the model with less flexible catch deviates are 0.25, 3.35, and 1.5, respectively.

A time series of ratios of $F_{current}\!\big/\tilde{F}_{MSY}$, $B_{current}\!\big/\tilde{B}_{MSY}$, and $SB_{current}\!\big/S\tilde{B}_{MSY}$ (Figure 44 and Figure 45) indicates the trend in the fishery towards higher levels of fishing pressure and higher impacts of fishing. F is estimated to remain well below F_{MSY}, but the estimated recruitment declines are driving the estimated biomass towards B_{MSY}. B_{2006} is estimated to be slightly below B_{MSY}.

6.4.7   Alternative structural scenarios

A set of structural uncertainty scenarios that was run before the problem with the effort deviates was resolved, may be used to compare some of the sources of structural uncertainty in the model.

Considerable uncertainty is evident with respect to all the management parameters $SB_{2004-2006}$ / SB_{MSY}, $B_{2004-2006}$ / B_{MSY}, and $F_{2004-2006}$ / F_{MSY} (Figure 46). The uncertainties between spawning biomass and fishing mortality are strongly correlated.

Comparing the effects of different components indicates that assumptions about steepness had the most effect on management parameters (Figure 47 to Figure 49), giving more pessimistic outcomes for steepness of 0.75 than for 0.95. The effective sample size multiplier for length frequency data was also influential.

7   Discussion and conclusions

The current stock assessment represents a major reappraisal of the underlying model structure used in the previous assessments of south Pacific albacore (Langley and Hampton 2005, Langley and Hampton 2006), which themselves represented a major reappraisal of previous assessments (Hampton 2002, Labelle and Hampton 2003).

Many of the changes examined in this assessment were prompted by a conflict observed (Langley and Hampton 2005, Langley and Hampton 2006) between the length frequency and CPUE data, given the way they were treated in the model. Reappraisal of the two main datasets used in the model (CPUE and length frequency) was recommended. Average size of fish caught has progressively increased (with some variation) since the 1970's, while CPUE has declined. If the declining CPUE was due to declining biomass, and if this declining biomass was due to fishing, then smaller fish sizes would be expected. Such conflicts can substantially bias a model, as it searches for parameter values that will accommodate both features at once. A symptom sometimes seen in these situations is that the model inflates the overall biomass, and uses recruitment to make the biomass trend follow the CPUE. Inflating the biomass estimate reduces the estimated fishing pressure, which helps the model to explain changes in length frequency that do not match what would be expected if fishing pressure was driving the biomass trend.

In developing this stock assessment we have made a number of changes to model configuration in order to try to reduce the conflict between the length frequency and CPUE data. We have changed the model's spatial and fishing fleet structure, incorporated new data, removed other data, and changed the model parameterization, to incorporate more of the features observed in data from the south Pacific albacore fishery. In doing so, the equilibrium unexploited biomass estimate (B_0) has been reduced by 70% from the 2006 assessment value of 2,124,000 mt, and the current biomass estimate ($B_{2004-2006}$) has also been reduced by 70%, from 1,405,000 mt ($B_{2000-2002}$). Estimated fishing pressure has increased in parallel. The model diagnostics and the likelihood indicate that the model fits the data better than the previous configuration.

However, it is evident that substantial conflict remains in the data, and that temporal trends remain in the longline length frequency data of a number of fisheries, including early trends involving the distant water longline fisheries, and more recent trends involving many fisheries. Problems are evident in the model diagnostics, such as trends in effort deviates, large length frequency residuals, and steep increases in estimated catchability for several fisheries at the end of the time series. In addition, some parameter estimates appear unrealistic, such as the tapering distribution of length at age as fish grow, and the narrow range of sizes for old fish. Attempts to reduce the impact of the increasing size of fish in the catch, by introducing time splits into selectivity and by reducing the weight given to length frequency data, generally resulted in estimates with lower biomass and higher fishing pressure. However, such changes would increase the recent high fishery impact, which already seems inconsistent with the high proportion of old (large) fish in the longline catch.

The size data indicate that there is still a substantial proportion of large adult fish in the population, which would not be the case if the very high estimated fishing mortalities on these age classes were sustained over the long-term.

7.1   Biomass trends

Two major features are evident in the catch per unit effort data. These are the decline between 1960 and 1975, and the steep decline after 1995.

Similar early declines in CPUE are often seen in longline fisheries. They usually (as in this case) occur at fishing pressure too low to cause such a decline solely by removing fish. One suggested explanation is the 'stupid fish' hypothesis, in which the initially naïve fish population changes to become more wary of longlines. The model accommodates this first decline by estimating initial equilibrium recruitment that is very high relative to mean recruitment. As recruitment returns to the average, biomass and expected longline CPUE also decline. Using recruitment rather than fishing to drive down the biomass means that the decline in longline-vulnerable biomass is also experienced by all other age classes. Using a high recruitment deviate to set the initial

equilibrium, and to drive this decline, isolates the initial decline somewhat from the rest of the model.

The second decline is more problematic. It is driven by a decline in the standardized Chinese Taipei CPUE. Again, the decline is too steep to be accounted for by fishing pressure, even though total catch does increase considerably over this period, so again the model uses recruitment to lower the exploitable biomass. In this case (assuming that recruitment did not actually decline) the conflict may be occurring for several reasons. First, a CPUE decline may be expected given higher catches, but is likely to be exaggerated. Chinese Taipei catches of bigeye and swordfish have increased recently (as have Korean catches), suggesting that multi-species targeting may be reducing albacore catch rates. Second, the distant water longline fisheries have been targeting larger fish in recent years, particularly in the south, but the estimated selectivity is pulled down by the smaller fish caught before 1980. The youth-biased selectivity profile gives the observed CPUE decline more 'leverage' to force down overall biomass in the model, since depletion of younger fish implies higher fishing pressure than does similar depletion of old fish. Third, the remaining conflict between the increasing catch and declining CPUE on the one hand, and the increasing fish size observed in a number of fisheries on the other, may be inflating the overall biomass and reducing fishing mortality .

7.2   Changes to the model

The main factors considered in the new assessment were as follows.

The appropriate spatial stratification of the model was considered. This resulted in the inclusion of an additional spatial component to the east, and moving the central division north by 5 degrees to 25 degrees of latitude. The first change allowed selectivity to be estimated separately for the eastern areas. The second change allowed selectivity estimates to better accommodate observed spatial patterns of length frequency distribution (Langley and Hoyle 2008).

The appropriate stratification by flag was also considered, resulting in separation by flag of the Japanese and Korean longline fleets. This change was justified by evidence for different patterns in the length frequency (Langley and Hoyle 2008) and catch per unit effort (Bigelow and Hoyle 2008) data for the two fleets. Taken together, the main effect of these three changes was to the timing of some recruitment estimates, and to increase the early biomass relative to later biomass estimates. At this stage the Japanese and Korean CPUE data was not being used, so the large observed effect of dividing these fisheries was due to separating the length frequency data.

Steps were also taken to improve the data inputs to the model. Standardized CPUE data were introduced for the three distant water longline fleets (Bigelow and Hoyle 2008), and applied without catchability deviates. Previously, only the unstandardized Chinese Taipei CPUE was used without catchability deviates. This change increased the weight given to CPUE data compared to length frequency data, and resulted in the model following the CPUE trend more closely. The model is now fitting to three standardized time series (division into seasons does not change the weight) with 1010 data points, compared to 736 quarterly catch rates in the 2006 assessment. However, only Chinese Taipei contributes significant CPUE data since the early 1990s, so the model is actually fitting to less CPUE data than previously during this period. The CPUE standardization is an important improvement to the stock assessment, and the standardization should be repeated with new data for future assessments. Attention should also be given to possible effects of targeting changes, and apparent anomalies in several time series around 1990.

Removing length frequency data sampled in Pago Pago before 1971, due to its distinctive distribution and our inability to find documentation of the sampling approaches used (Hoyle *et al.*

2008), significantly changed the overall growth rate and population trajectory. These samples had a narrower size distribution than those observed later, and the change appears to have reduced the conflict between the CPUE and length frequency data in the early part of the time series. This decision can be re-visited if more information about sampling procedures becomes available, so that the data can be modelled appropriately.

Model parameterization was also examined. Catchability deviates were estimated every 6 months instead of every two years, and allowed more flexibility. These changes were made to reduce to reduce the risk of bias from unpredictable information. First, large changes in catchability have been observed in some fisheries, such as the New Zealand and Australian longline fisheries, associated with changes in targeting and fishing practices (Unwin *et al.* 2005). Second, fisheries that are composites of a number of fleets, such as the 'other' fisheries present in each region, may change overall catchability unpredictably as relative effort changes among fleets with different catchabilities. Third, small fisheries with fewer vessels can change catchability rapidly as they develop, as catch reporting coverage rates change, and as vessel sizes, equipment, and personnel change. Standardization is suggested as an approach that can help to deal with these changes. Fourth, catch rates will tend to vary more with environmental conditions in fisheries that sample smaller areas. Finally, effort data had been invented for some fisheries where it was missing, such as the early years of the New Zealand troll fishery. Given these issues, it may be appropriate in future to vary the weight given to length frequency data from different fisheries, depending on how features like those referred to above affect each fishery.

Seasonality was introduced into selectivity. Albacore are highly migratory both on a seasonal basis, and with age and sexual maturity (Jones 1991), with smaller fish caught in the south, and north-south movements occurring at certain times of year. East–west movements may also occur, as they appear to in the north Pacific. The sizes of fish in the catch vary both seasonally and spatially (Langley and Hoyle 2008). The single region model assumes that fish form a single uniform pool, so seasonal selectivity is needed to extract fish of the correct size from the population, and (more importantly) to calculate the expected length frequency distribution appropriately.

For similar reasons, selectivity was permitted to decline with increasing age in all fisheries except the three seasonal fisheries in which the largest fish were observed. Allowing selectivity to decline with age is necessary when applying a single region model to a spatially subdivided fishery in which size distributions vary. Longline fisheries in the south catch more small fish and fewer large fish than northern longline fisheries, so southern selectivity is best modelled with a selectivity peak at younger age, followed by a decline. The choice of which fisheries to constrain to be non-declining was somewhat ad hoc and should be re-visited at a later date, by examining residuals rather than by simply checking fish sizes. As well as selectivity, fish size depends on the size of the fish in the population at the time, which needs to be taken into account.

Standardized CPUE from the New Zealand troll fishery (Unwin *et al.* 2005), which have not been used in previous assessments, were included in the model. These data are only available for a relatively short period (1993 to 2004) but, since the fishery takes small fish two to four years old, provided useful information about both short term recruitment variation and long term recruitment trends. The standardized CPUE data indicated considerable variability in recruitment. Adding these standardized data to the model did not change the timing of estimated recruitments, but increased the variability between peaks and troughs. This suggests that the information about recruitment timing in these data is not inconsistent with information about recruitment timing from other data in the model. Peaks in the standardized CPUE data were consistent with peaks in the New Zealand troll fishery length frequency data (Unwin *et al.* 2005).

Adding the New Zealand troll data also resulted in a more stable long-term recruitment trend, since the data do not support a recent decline in recruitment. This is a useful piece of information, since it counteracts (to some extent) the tendency of the model to use recruitment to drive abundance trends. The main qualification would be if the New Zealand troll catch rates were strongly affected by hyperstability, a process in which catch rates remain stable while biomass declines. This can occur in a search fishery where communication is important, although the standardization attempted to account for this. Hyperstability can also occur when fish tend to aggregate in the most favourable habitat. Variation in availability is another issue that can complicate the interpretation of CPUE data from a spatially localised fishery, but this can be dealt with by reducing the penalty on the effort deviates. A longer time series of standardized data from this fishery would be a useful addition to the stock assessment, particularly for recent years. Investigation of ways to include catch rate data from before 1993 in the model is also suggested.

These observations support the need to maintain the current sampling of the troll fishery around New Zealand (e.g. Griggs 2004) and the sampling 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.

Given the problems with length frequency data from the distant water longline fisheries, the effective sample size allocated to all length frequency data, except New Zealand troll data, was reduced by 50%. This reduced the estimated biomass and enabled the modelled exploitable biomass to track the CPUE more closely. Given the severity of the data problems, further effective sample size reduction should be examined, particularly for the southern longline fisheries. Length frequency sample size reductions should also be examined for domestic fisheries that have changed target (such as the New Zealand longline fishery) and the composite 'Other' fisheries in which the relative sample sizes of different components (which may have different selectivities) may change.

7.3   Sensitivity analyses

Other sensitivity analyses were undertaken to explore the impact of assumptions about the stock recruitment relationship (steepness) and increased fishing efficiency. Steepness is unknown and very difficult to estimate from fisheries data, and so constitutes a relatively intractable source of uncertainty. Alternative values should always be considered in a stock assessment. Over a plausible range of steepness values (0.7 to 0.98), the Fmultiplier varied by ± 50%. The albacore stock assessment is very sensitive to assumptions about steepness (Hoyle 2008) because the spawning biomass at maximum sustainable yield is very low for albacore, at 18% of spawning biomass at MSY.

Effort creep, modelled at 0.5% per year, also reduced the F multiplier. Effort creep is very likely to be affecting even the standardized longline effort for south Pacific albacore, and further work should be carried out to determine an appropriate level to include in the model. At some life stages, albacore tend to aggregate at oceanographic fronts (Chen *et al.* 2005, Langley 2004, Laurs *et al.* 1977), and the technology to detect fronts has improved dramatically in recent years. Preferred environmental conditions also vary with age, and improved ability to target larger fish may help to explain the increasing average size of albacore caught in recent years. Such technological advances may be capable of generating quite large increases in fishing mortality.

An array of sensitivities (not presented here) was carried out with all combinations of ± the Australian growth curve, estimated effort creep, natural mortality of 0.4 and 0.45, steepness of 0.75 and 0.95, starting year of 1960 and 1971, and with and without time splits. Results showed a wide range of variation in biomass, fishing mortality, and management parameters, indicating a

high degree of structural uncertainty. However, all were affected by the same bias due to the data conflict, so do not adequately reflect the true level of uncertainty.

Limited tagging data were available for inclusion into the current assessment (a total of 138 recoveries). These data provide useful information about movement, harvest rate, and growth rates. 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, and SPC is scheduled to begin a 2 year tagging program in the New Zealand troll fishery in 2009. However, the implementation of a programme targeting adult albacore would require considerable development of tagging techniques for the species, given the difficulty of obtaining, and releasing, live adults. Model development is also required to permit more flexibility in the underlying assumptions, and to use the tagging data to inform growth rate estimates.

Tag reporting rates estimated in this assessment are considerably lower than those from the previous assessments reflecting the higher fishing mortality rates. There are problems in estimating these reporting rates in a single region model, given that the model has difficulty dealing with migration and mixing. However, the rate of decline in tag returns is relatively robust to these problems, and the final version of the model with lower biomass fitted the data more successfully than did the earlier configurations.

7.4   Management implications

Estimates of fishery impacts on biomass ($B_{current}/B_{current,F=0}$) have progressively increased between the 2003 assessment (3%), the 2005 (9%) and 2006 (10%) assessments, and this assessment (30%), as model configurations have progressively changed, and the estimated fishing mortality has increased. Correspondingly, estimates of MSY from the respective assessments have declined (more than 300,000 mt, 183,000 mt, 181,000 mt, and now 64,000 mt).

Based on the evident fitting problems in this assessment, and comparisons between these four assessments, there remains considerable uncertainty regarding both the overall stock size and the current level of fishing mortality. Therefore, it is important to reiterate statements made in 2005, to qualify the results of the current and past assessments with other observations made directly 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). The highest catch rates for albacore in the subequatorial area are relatively localised and 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) may indicate local scale depletion of the stock (Langley 2004). This suggests that a relatively low level of exploitable biomass is accessible to these fisheries, and that movement rates into the EEZ are lower than the peak levels of catch. However, it may be useful to revisit the

assumption of localized depletion, in view of the much lower stock size estimated in the present assessment, and the likelihood that overall stock size has declined in recent years.

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 latitudinal range, albeit in opposite hemispheres, and support longline and surface fisheries. Annual catches from the north Pacific albacore fishery have fluctuated between 40,000 and 120,000 mt since the 1950s, with approximately half the catch taken by the longline fishery in recent years (ISC 2007). Recent spawning stock biomass is estimated to be about 150,000 mt, above a long-term average of 100,000 mt. Recent fishing mortality rates on the adult component of the stock were high (about 0.75), and recent catches are about 60,000 mt.

These auxiliary observations lend support to the hypothesis that, with the current pattern of age-specific selectivity, the south Pacific albacore stock may not support a fishery much above the current level – a level that has increased in recent years. There remains a high level of uncertainty regarding the magnitude of the stock size, and current fishing mortality.

The current assessment estimates moderate levels of exploitation ($B_{2004-2006}\big/B_{2004-2006,F=0}$ = 0.70, and $F_{2004-2006}\big/\tilde{F}_{MSY}$ = 0.44). Nevertheless, given the estimated decline in recruitment, the current level of longline catch is estimated to be having a relatively large impact on the portion of the stock vulnerable to the longline fishery. The magnitude of this impact is uncertain, and varies among fisheries, although the assessment indicates that the current level of impact is between 30 and 70%, depending on the fishery. It has increased sharply in recent years. The impact on the spawning biomass component of the stock is approximately 50%.

The model estimates that increasing effort to F_{MSY} would yield only slightly more catch in the long term (equilibrium yield at current effort 55,000 mt; MSY 64,000 mt). Higher yields would require more fishing effort, resulting in lower adult biomass and, at the current exploitation pattern of the fishery, a greater decline in the level of longline exploitable biomass. Thus, any consideration of management objectives and performance indicators for the south Pacific albacore fishery needs to also consider the economics of those longline fisheries targeting albacore in the region.

7.5   Conclusions and recommendations

Stock status:
- Lower levels of stock size and MSY than in previous assessments appear to be more realistic, since many sources of potential bias have been removed.
- However, clear evidence of bias remains, and there is considerable uncertainty about current levels of fishing mortality.
- The stock status indicator $F_{2004-2006}/F_{MSY}$ is strongly affected by structural uncertainty in the model, some of it related to the failure to model apparent increasing length selectivity through time, and some related to uncertainty about whether the recent large decline in standardized Chinese Taipei CPUE accurately reflects a decline in biomass.
- Models that permit selectivity to vary through time, to account for the observation of increasing fish size in the longline catch, tend to give lower biomass relative to B_{MSY}, and higher fishing mortality relative to F_{MSY}, throughout the time series.
- Models that give less weight to the recent decline in Chinese Taipei CPUE tend to estimate higher biomass relative to B_{MSY}, and lower fishing mortality relative to F_{MSY}, in recent years.

- Estimates of $F_{2004\text{-}2006}/F_{MSY}$ and $SB_{2004\text{-}2006}/SB_{MSY}$ are highly variable between model configurations.
- In all credible model configurations, $F_{2004\text{-}2006}$ is estimated to be below F_{MSY}, $B_{2004\text{-}2006}$ is estimated to be above B_{MSY}, and $SB_{2004\text{-}2006}$ is estimated to be above SB_{MSY}.
- There is no indication that current levels of catch are not sustainable, particularly given the age selectivity of the fisheries.
- Given the uncertainty in the results, the evident sources of potential bias, and the less optimistic implications of the results than in previous assessments, further efforts to improve the model should be considered a high priority.

Model development:
- Develop stock assessment model to improve ability to change selectivity through time, possibly with a covariate.
- Examine all available operational data, to improve understanding of why and how selectivity changes.
- Standardize, and use in the model, a longer time series of New Zealand troll data.
- Carry out biological research to provide better prior information for the growth curve.
- Implement prior distribution, and (or) fit to data, for age at length in MFCL. Integrated estimation of the growth curve is desirable.
- Investigate alternative growth curve parameterizations, such as the Richards curve.
- Investigate length-based selectivity, which may help to correct the narrow estimated distribution of length at age.
- Independent estimates of F would be very useful, and options to obtain these from tagging programs should be explored. Tagging programs should include enhanced efforts to estimate tag return rates, tag loss, and tagging-related mortality.
- Alternative methods for modelling tag returns within MFCL should be explored, given the violation of mixing assumptions associated with the single region model.
- Multi-region models should be explored further.
- Investigate an integrated assessment of North and South Pacific albacore. While separate northern and southern stocks should be maintained as the fundamental stock structure hypothesis, such an integrated assessment may improve the assessment of both stocks because of enhanced overall information on stock dynamics and sharing of common biological characteristics.

8   Acknowledgements

9   References

Bigelow, K. A. and Hoyle, S. D. (2008). Standardized CPUE for distant-water fleets targeting south Pacific albacore. No. WCPFC SC4 ME-WP-3.)

Chen, I. C., Lee, P. F., and Tzeng, W. N. (2005). Distribution of albacore (Thunnus alalunga) in the Indian Ocean and its relation to environmental factors. *Fisheries Oceanography* **14**, 71-80.

Farley, J. H. and Clear, N. P. (2008). Albacore tuna: investigation of size monitoring, age composition, and spawning activity in the ETBF. No. 2006/826 (CSIRO.)

Fournier, D. A., Hampton, J., and Sibert, J. R. (1998). MULTIFAN-CL: a length-based, age-structured model for fisheries stock assessment, with application to South Pacific albacore, Thunnus alalunga. *Canadian Journal of Fisheries and Aquatic Sciences* **55**, 2105-2116.

Francis, R. I. C. C.(1992). Use of risk analysis to assess fishery management strategies: A case study using orange roughy (*Hoplostethus atlanticus*) on the Chatham Rise, New Zealand. *Canadian Journal of Fisheries and Aquatic Sciences* **49**, 922-930.

Griggs, L. (2004). Monitoring the length structure of New Zealand commercial landings of albacore during the 2003/04 fishing year. No. Working paper BIO-6. 17th Standing Committee on Tuna and Billfish. 9–18 August 2004. Majuro, Republic of Marshall Islands.)

Hampton, J.(2002). Stock assessment of albacore tuna in the south Pacific Ocean. *15th Meeting of the Standing Committee on Tuna and Billfish. Honolulu, Hawaii, ALB-1* **31**.

Hampton, J. and Fournier, D. A. (2001). A spatially disaggregated, length-based, age-structured population model of yellowfin tuna (Thunnus albacares) in the western and central Pacific Ocean. *Marine & Freshwater Research* **52**, 937-963.

Harley, Shelton and Maunder, Mark N. (2003). A simple model for age-structured natural mortality based on changes in sex ratios. IATTC, 4th Meeting of the Scientific Working Group, La Jolla, USA, May 19-21 2003.

Helu, L. (2004). An evaluation of recent trends in the domestic longline fisheries operating in the south Pacific Ocean and the evaluation of a proposed alteration to the area strata presently used in stock assessment for albacore. (Working paper SA-8. 17 thStanding Committee on Tuna and Billfish. 9û18 August 2004. Majuro, Republic of Marshall Islands.)

Hoyle, S. D. (2008). Adjusted biological parameters and spawning biomass calculations for south Pacific albacore tuna, and their implications for stock assessments. No. WCPFC SC4 ME-WP-2.)

Hoyle, S. D., Sharples, P., and Nicol, S. (2008). The influence of changes in length frequency sampling methodologies on the south Pacific albacore stock assessment. No. WCPFC-SC4-2008/ST-IP-3.)

Jones, J. B.(1991). Movements of Albacore Tuna (Thunnus-Alalunga) in the South-Pacific - Evidence from Parasites. *Marine Biology* **111**, 1-9.

Kleiber, P., Hampton, J., and Fournier, D. A. (2006). MULTIFAN-CL User's Guide.

Labelle, M. and Hampton, J. (2003). Stock assessment of albacore tuna in the South Pacific Ocean. *16th Meeting of the Standing Committee on tuna and Billfish, Mooloolaba, Queensland*, 9-16.

Labelle, M., Hampton, J., Bailey, K., Murray, T., Fournier, D. A., and Sibert, J. R. (1993). Determination of age and growth of south Pacific albacore (Thunnus alalunga) using three methodologies. *Fishery Bulletin* **91**, 649-663.

Langley, A. (2004). An examination of the influence of recent oceanographic conditions on the catch rate of albacore in the main domestic longline fisheries. (Working Paper SAû4. Seventeenth Meeting of the Standing Committee on Tuna and Billfish. Majuro, Marshall Islands. 9 thû18 thAugust 2004.)

Langley, A. and Hampton, J. (2005). Stock assessment of albacore tuna in the South Pacific Ocean. *WCPFC SC1 SA WP-3*.

Langley, A. D. and Hampton, J. (2006). An update of the stock assessment for South Pacific albacore tuna, including an investigation of the sensitivity to key biological parameters included in the model. In 'Western and Central Pacific Fisheries Commission, Scientific Committee 2*'*.).

Langley, A. D. and Hoyle, S. D. (2008). Report from the stock assessment preparatory workshop, Noumea, February 2008. No. WCPFC SC4 SA-IP-5 (SPC: Nouméa, New Caledonia.)

Laurs, R. M., Yuen, H. S. H., and Johnson, J. H. (1977). Small-scale movements of Albacore, Thunnus alalunga, in relation to Ocean features as indicated by ultrasonic tracking and oceanographic sampling. *Fish. Bull. NMFS/NOAA* **75**, 347-355.

Lawson, T. A. (1997). Review of catch estimates for Taiwanese distant water longliners. No. Oceanic Fisheries Programme Internal Report No. 31 (Oceanic Fisheries Programme, Secretariat of the Pacific Community, Noumea, New Caledonia.)

Leroy, B. and Lehodey, P. (2004). Note on the growth of the south Pacific albacore. No. Working paper INFO-BIO-2. (17th Standing Committee on Tuna and Billfish. 9-18 August 2004. Majuro, Republic of Marshall Islands.)

Maunder, M. N., Watters, G. M., and Inter-American Tropical Tuna Commission. (2003). 'A-SCALA: An Age-structured Statistical Catch-at-length Analysis for Assessing Tuna Stocks in the Eastern Pacific Ocean.' (Inter-American Tropical Tuna Commission.)

Murray, T.(1994). A review of the biology and fisheries for albacore, Thunnus alalunga, in the South Pacific Ocean. *Interactions of Pacific tuna fisheries. Edited by RS Shomura, J. Majkowski, and S. Langi. FAO Fish. Tech. Pap*, 188-206.

Ramon, D. and Bailey, K. (1996). Spawning seasonality of albacore, Thunnus alalunga, in the South Pacific ocean. *Fishery Bulletin* **94**, 725-733.

Unwin, M., Richardson, K., Uddstrom, M., Griggs, L., Davies, N., and Wei, F. (2005). Standardized CPUE for the New Zealand albacore troll and longline fisheries, WCPFC-SC-2005: SA WP-5.).

10 Tables:

Table 1: A description of the fisheries included in the assessment.

Fishery	Fishery label	Region	Method	Flag	Catch	Effort
1	JP,JPDW LL 1	1	Longline	Japan	Number	Hooks (100s)
2	KR LL 1	1	Longline	Korea	Number	Hooks (100s)
3	TWDW LL 1	1	Longline	Chinese Taipei	Number	Hooks (100s)
4	AU LL 1	1	Longline	Australia	Number	Hooks (100s)
5	NC LL 1	1	Longline	New Caledonia	Number	Hooks (100s)
6	FJ LL 1	1	Longline	Fiji	Number	Hooks (100s)
7	OTHER LL 1	1	Longline	Other	Number	Hooks (100s)
8	JP,JPDW LL 2	2	Longline	Japan	Number	Hooks (100s)
9	KR LL 2	2	Longline	Korea	Number	Hooks (100s)
10	TWDW LL 2	2	Longline	Chinese Taipei	Number	Hooks (100s)
11	AS,WS LL 2	2	Longline	American Samoa, Samoa	Number	Hooks (100s)
12	TO LL 2	2	Longline	Tonga	Number	Hooks (100s)
13	PF LL 2	2	Longline	French Polynesia	Number	Hooks (100s)
14	OTHER LL 2	2	Longline	Other	Number	Hooks (100s)
15	JP,JPDW LL 3	3	Longline	Japan	Number	Hooks (100s)
16	KR LL 3	3	Longline	Korea	Number	Hooks (100s)
17	TWDW LL 3	3	Longline	Chinese Taipei	Number	Hooks (100s)
18	AU LL 3	3	Longline	Australia	Number	Hooks (100s)
19	NZ LL 3	3	Longline	New Zealand	Number	Hooks (100s)
20	OTHER LL 3	3	Longline	Other	Number	Hooks (100s)
21	JP,JPDW LL 4	4	Longline	Japan	Number	Hooks (100s)
22	KR LL 4	4	Longline	Korea	Number	Hooks (100s)
23	TWDW LL 4	4	Longline	Chinese Taipei	Number	Hooks (100s)
24	OTHER LL 4	4	Longline	Other	Number	Hooks (100s)
25	TROLL 3	3	Troll	New Zealand, United States	Number	Days
26	TROLL 4	4	Troll	New Zealand, United States	Number	Days
27	DN 3	3	Drift net	Japan, Chinese Taipei	Weight	Days
28	DN 4	4	Drift net	Japan, Chinese Taipei	Weight	Days
29	OTHER LL 5	5	Longline	Other	Number	Hooks (100s)
30	OTHER LL 6	6	Longline	Other	Number	Hooks (100s)

Table 2: Initial values for the biological parameters included in the model.

Parameter	Value	
Proportion mature at age (yrs)	0, 0, 0, 0, 0.23, 0.57, 0.88, 1, 0.90, 0.81, 0.72, 0.64, 0.56, 0.49, 0.43, 0.37, 0.32, 0.274, 0.24, 0.20	Fixed
Length-wt relationship	a = 6.9587e-06, b =3.2351	Fixed
Growth (Von bertalanfy)	$L_{t=1}$ = 45 cm, k = 0.2, Linf = 100 cm	Estimated
Natural mortality	0.374, 0.374, 0.374, 0.374, 0.374, 0.409, 0.442, 0.436, 0.430, 0.424, 0.418, 0.413, 0.409, 0.404, 0.400, 0.397, 0.394, 0.391, 0.388, 0.386	Fixed

Table 3: Main structural assumptions used in the base case model.

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 for all fisheries (except the New Zealand troll fishery) is assumed to be 0.05 (NZ troll = 0.1) times actual sample size with a maximum effective sample size of 50 (NZ troll = 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. Maximum reporting rate constrained to be <=0.9. All reporting rates constant over time.
Tag mixing	Tags assumed to be randomly mixed 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 (steepness = 0.9).
Initial population	Equilibrium age structure in the region as a function of the estimated natural mortality and the first three years of fishing mortality.
Age and growth	20 annual age-classes, with the last representing a plus group. 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.
Catchability	Seasonal variation for troll and driftnet fisheries. All fisheries without effort based on standardized CPUE have structural time-series variation, with random steps (catchability deviations) taken every 6 months. Catchability deviations constrained by a prior distribution with (on the log scale) mean 0 and SD 0.7.
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	Fixed with mean 0.4. Age specific variation.
Movement	Not relevant for this model. Fish are assumed to be distributed across all regions.

Table 4: Tasks recommended by the February preparatory meeting, and whether they were carried out for the stock assessment.

	Option	Suggested status	Base case & scenarios?	Sensitivity analysis?
1	Add sex ratio and maturity info to base case	base case	Yes + additional parameters	ME-WP-
2	Investigate length-weight relationship	data analysis / base case	No	Yes
3	Rerun biological sampling analyses with steepness fixed at 0.75 and 0.9	sensitivity analysis	Scenarios	Yes
4	Loosen catchability deviates on domestic longline fisheries	base case	Yes	Yes
5	NZ troll - use stdized data, split fishery 1982, 1993; remove deviates post 1982 or 1993	sensitivity analysis	Latter period	Yes
6	Apply size-based selectivity to small fish in SS2	sensitivity analysis	No	No
7	Downweight early LL LF from all DW fleets, in several time scenarios	sensitivity analysis	Downwt all LF	All LF
8	Apply criteria to check for representative length frequency samples in all DW LL	data analyses / MFCL runs	Yes.	Yes
9	Split LL fisheries by season	base case	Yes	Yes
10	Examine consequences of moving N/S division north 5 degrees	sensitivity analysis / base case	Yes	Yes
11	Examine correlation between year and longitude effects in GLM on size	data analysis	No	No
12	Consider splitting southern LL fisheries at longitudes 160 and 210	data analyses / MFCL runs / base case	No	No
13	Standardize Pago-Pago data	data analysis	Yes	Yes
14	Examine feasibility of pooling DW fisheries, using Pago-Pago CPUE	data analyses / MFCL runs / base case	Not feasible	Not feasible
15	Reconsider long term trends in size given Pago-Pago information on fishing practices	data analyses / MFCL runs / base case	Scenarios	Yes
16	Permit selectivity to decrease with age in some longline fisheries	sensitivity analysis / base case	Yes	Yes
17	Iterative re-weighting to determine efective sample size for LF and CPUE data	sensitivity analysis / base case	No	No
18	Explore multi-region model	MFCL runs	No	No

Table 5: For each progressive change in model configuration, likelihood, number of parameters, and relationship between estimated current biomass and unfished biomass. The row 'Sel in 3 fisheries=1, fix M' is in bold, because it is used as a comparator for the sensitivity analyses.

Model configuration	-log Likelihood	# pars	$B_{2004\text{-}2006}$ / B_{MSY}	Fmult	M	k	Lmax
2006 setup	359789.1	2797	1.33	42.06	0.42	0.213	102.8
Add east, separate JP, KR	422486.3	3636	1.34	44.07	0.40	0.218	102.1
25 degree boundary	434586.3	3883	1.40	42.29	0.31	0.226	100.1
Start in 1960	434736.2	3754	1.37	57.01	0.32	0.231	99.7
Clean catch data	434720.8	3757	1.38	50.46	0.31	0.233	99.7
Add LL glm	430554.0	3711	1.30	56.37	0.36	0.240	99.9
Clean early LF data	383187.1	3711	1.09	41.18	0.63	0.333	100.5
Loosen q deviates	384314.6	4252	0.83	26.87	0.65	0.326	100.9
Sel. can decline with age	384381.0	4252	0.90	14.39	0.54	0.359	99.7
Seasonal fisheries	386489.8	5294	0.91	30.64	0.99	0.321	105.7
Sel =1 in 3 fisheries, fix M	**386313.2**	**5293**	**1.19**	**5.37**	**0.40**	**0.373**	**100.3**
Length weight relationship	386309.0	5293	1.19	5.42	0.40	0.373	100.3
Australian growth curve	386276.2	5291	1.13	3.78	0.40	0.321	102.9
NZ troll glm	385620.5	5255	1.29	3.73	0.40	0.371	100.6
Steepness=0.7	386314.8	5293	1.12	2.76	0.4	0.377	100.3
Steepness=0.98	386313.8	5293	1.33	8.43	0.4	0.377	100.3
Effort creep	386270.0	5293	1.13	5.72	0.4	0.374	100.3
Down-weight LF data	341060.4	5293	1.21	4.36	0.4	0.378	100.1
Up-weight NZ troll LF	386878.6	5293	1.20	5.44	0.4	0.367	100.4
Estimate length at age 1	386353.7	5294	1.22	5.54	0.4	0.388	100.2
Selectivity split 1	370835.3	5409	1.12	3.86	0.4	0.382	100.4
Selectivity split 2	371380.9	5771	1.55	2.00	0.4	0.245	108.2
Selectivity split 3	372341.6	5760	1.51	1.37	0.4	0.312	105.3
Final Configuration	341191.3	5256	1.18	2.51	0.4	0.347	101.8
Final + repair effort deviates	344872.1	5637	1.26	2.28	0.4	0.383	101.1
Tighten q deviates	344830.9	4878	1.50	4.02	0.4	0.340	101.7

Table 6: Details of objective function components

Objective function component	
Number of parameters	5,637
Total catch log-likelihood	146
Length frequency log-likelihood	-350,443
Tag log-likelihood	493
Penalties	4,910
Total function value	- 344,872
Maximum gradient at termination	0.000015

Table 7: Contributions to the log-likelihood by the length frequency data of each fishery.

Method	Region	Flag	Season 1	2	3	4	ALL
Longline	R1	AU	−604	−1027	−423	−379	
		FJ	−2183	−3218	−3317	−3303	
		JP,JPDW	−5747	−5183	−8413	−5959	
		KR	−3724	−4581	−5028	−3911	
		NC	−4168	−4275	−4641	−4494	
		OT	−2427	−2928	−2855	−2563	
		TWDW	−6523	−5165	−5541	−5295	
	R2	AS,WS	−2007	−2220	−2377	−2176	
		JP,JPDW	−5325	−7647	−6323	−7051	
		KR	−6299	−5037	−5792	−6258	
		OT	−2960	−2754	−3144	−2016	
		PF	−3447	−2935	−3341	−3600	
		TO	−2852	−3279	−3196	−3238	
		TWDW	−7060	−4693	−5147	−6900	
	R3	AU	−1105	−1655	−1763	−1273	
		JP,JPDW	−2308	−6723	−6480	−1828	
		KR	−403	−2873	−2691	−912	
		NZ	−2179	−2289	−1271	−1414	
		OT	−525	−974	−1862	−859	
		TWDW	−361	−2423	−4393	−275	
	R4	JP,JPDW	−458	−2685	−2410	−1071	
		KR	−1881	−4113	−3334	−997	
		OT	−990	−1967	−2218	−1145	
		TWDW	−2947	−6790	−6846	−1092	
	R5	ALL	−447	−2802	−6064	−2180	
	R6	ALL	0	13.9	−1509	−741	
Troll	R3	ALL					−9105
	R4	ALL					−9018
Driftnet	R3	ALL					−1236
	R4	ALL					−621

Table 8. Description of symbols used in the yield analysis.

Symbol	Description
$F_{2004-2006}$	Average fishing mortality-at-age for 2004–2006
F_{MSY}	Fishing mortality-at-age producing the maximum sustainable yield (*MSY*)
$\tilde{Y}_{F_{2004-2006}}$	Equilibrium yield at $F_{2004-2006}$
$\tilde{Y}_{F_{MSY}}$ (or *MSY*)	Equilibrium yield at F_{MSY}, or maximum sustainable yield
$\tilde{B}_0$	Equilibrium unexploited total biomass
$\tilde{B}_{F_{2004-2006}}$	Equilibrium total biomass at $F_{2004-2006}$
$\tilde{B}_{MSY}$	Equilibrium total biomass at MSY
$S\tilde{B}_0$	Equilibrium unexploited adult biomass
$S\tilde{B}_{F_{2004-2006}}$	Equilibrium adult biomass at $F_{2004-2006}$
$S\tilde{B}_{MSY}$	Equilibrium adult biomass at MSY
$B_{2004-2006}$	Average current (2004–2006) total biomass
$SB_{2004-2006}$	Average current (2004–2006) adult biomass
$B_{2004-2006,F=0}$	Average current (2004–2006) total biomass in the absence of fishing.

Table 9. Estimates of management quantities for the base case and the sensitivity analysis with less flexible catchability deviates (as used in the 2006 assessment). 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	Base case	Tight catchability deviates
$\tilde{Y}_{F_{2004-2006}}$	mt per year	55,000	54,000
$\tilde{Y}_{F_{MSY}}$ (or *MSY*)	mt per year	64,000	75,000
$\tilde{B}_0$	mt	698,000	825,000
$\tilde{B}_{F_{2004-2006}}$	mt	465,000	618,000
$\tilde{B}_{MSY}$	mt	340,000	403,000
$S\tilde{B}_0$	mt	231,000	285,000
$S\tilde{B}_{F_{2004-2006}}$	mt	89,000	151,000
$S\tilde{B}_{MSY}$	mt	40,000	52,000
$B_{2004-2006}$	mt	428,000	605,000
$SB_{2004-2006}$	mt	121,000	174,000
$B_{2004-2006,F=0}$	mt	611,000	784,000
$B_{2004-2006}\big/\tilde{B}_0$		0.61	0.73
$B_{2004-2006}\big/\tilde{B}_{F_{2004-2006}}$		0.92	0.98
$B_{2004-2006}\big/\tilde{B}_{MSY}$		1.26	1.50
$B_{2004-2006}\big/B_{2004-2006,F=0}$		0.70	0.77
$SB_{2004-2006}\big/S\tilde{B}_0$		0.52	0.61
$SB_{2004-2006}\big/S\tilde{B}_{F_{2004-2006}}$		1.35	1.15
$SB_{2004-2006}\big/S\tilde{B}_{MSY}$		2.99	3.35
$SB_{2004-2006}\big/S\tilde{B}_{2004-2006,F=0}$		0.50	0.59
$\tilde{B}_{F_{2004-2006}}\big/\tilde{B}_0$		0.67	0.75
$S\tilde{B}_{F_{2004-2006}}\big/S\tilde{B}_0$		0.39	0.53
$\tilde{B}_{MSY}\big/\tilde{B}_0$		0.49	0.49
$S\tilde{B}_{MSY}\big/S\tilde{B}_0$		0.18	0.18
$MSY\big/\tilde{B}_{MSY}$ $MSY\big/\tilde{B}_{MSY}$		0.19	0.19
$F_{2004-2006}\big/\tilde{F}_{MSY}$		0.44	0.25
$\tilde{F}_{MSY}\big/F_{2004-2006}$ (*F multiplier*)		2.28	4.02
$\tilde{B}_{F_{2004-2006}}\big/\tilde{B}_{MSY}$		1.37	1.53
$S\tilde{B}_{F_{2004-2006}}\big/S\tilde{B}_{MSY}$		2.21	2.90
$\tilde{Y}_{F_{2004-2006}}\big/MSY$		0.86	0.72

11 Figures:
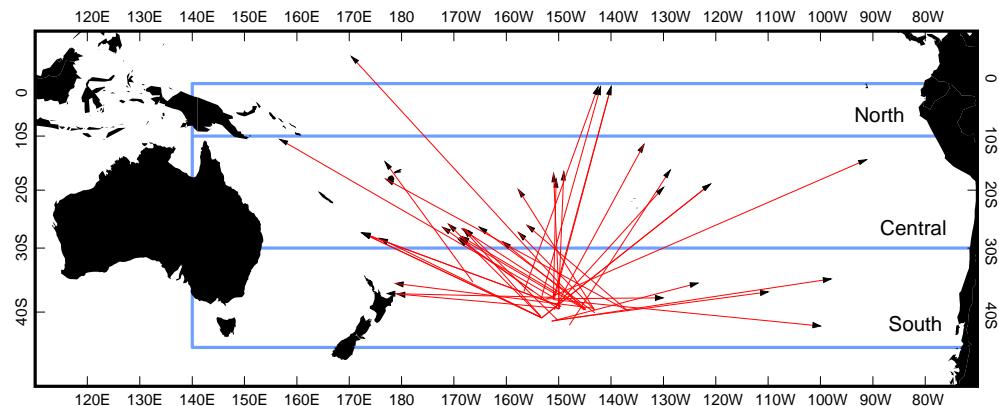
Figure 1. Movements of tagged South Pacific albacore (from Labelle & Hampton 2003).
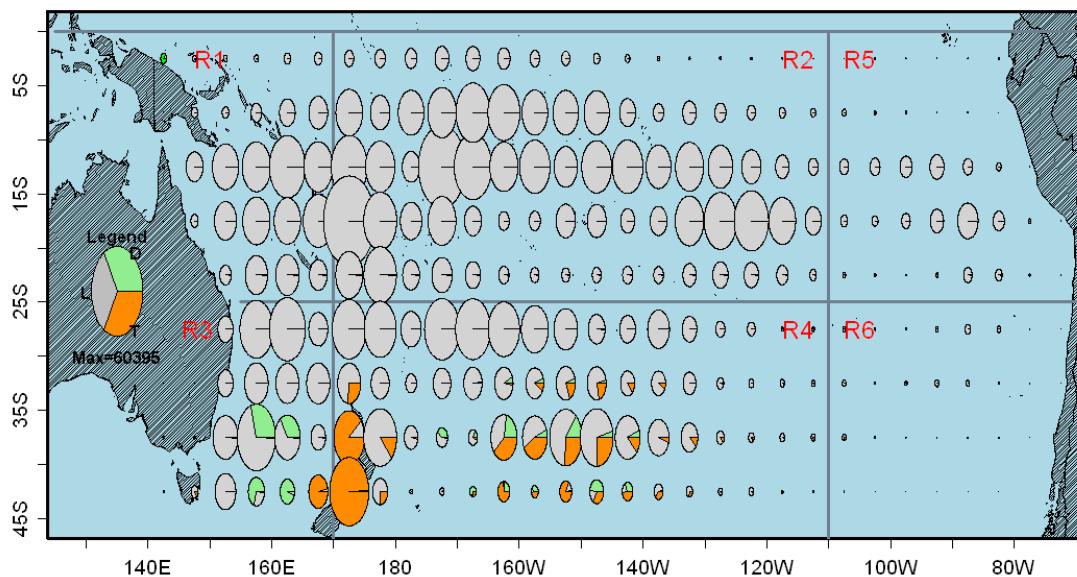
Figure 2: Total catch from 1960 to 2003 by 5 degree squares of latitude and longitude by fishing gear; longline (L), driftnet (G), and troll (T). The area of the pie chart is proportional to the total catch. The boundary of the stock assessment area is delineated by the black line and regional boundaries are delineated by the grey lines.
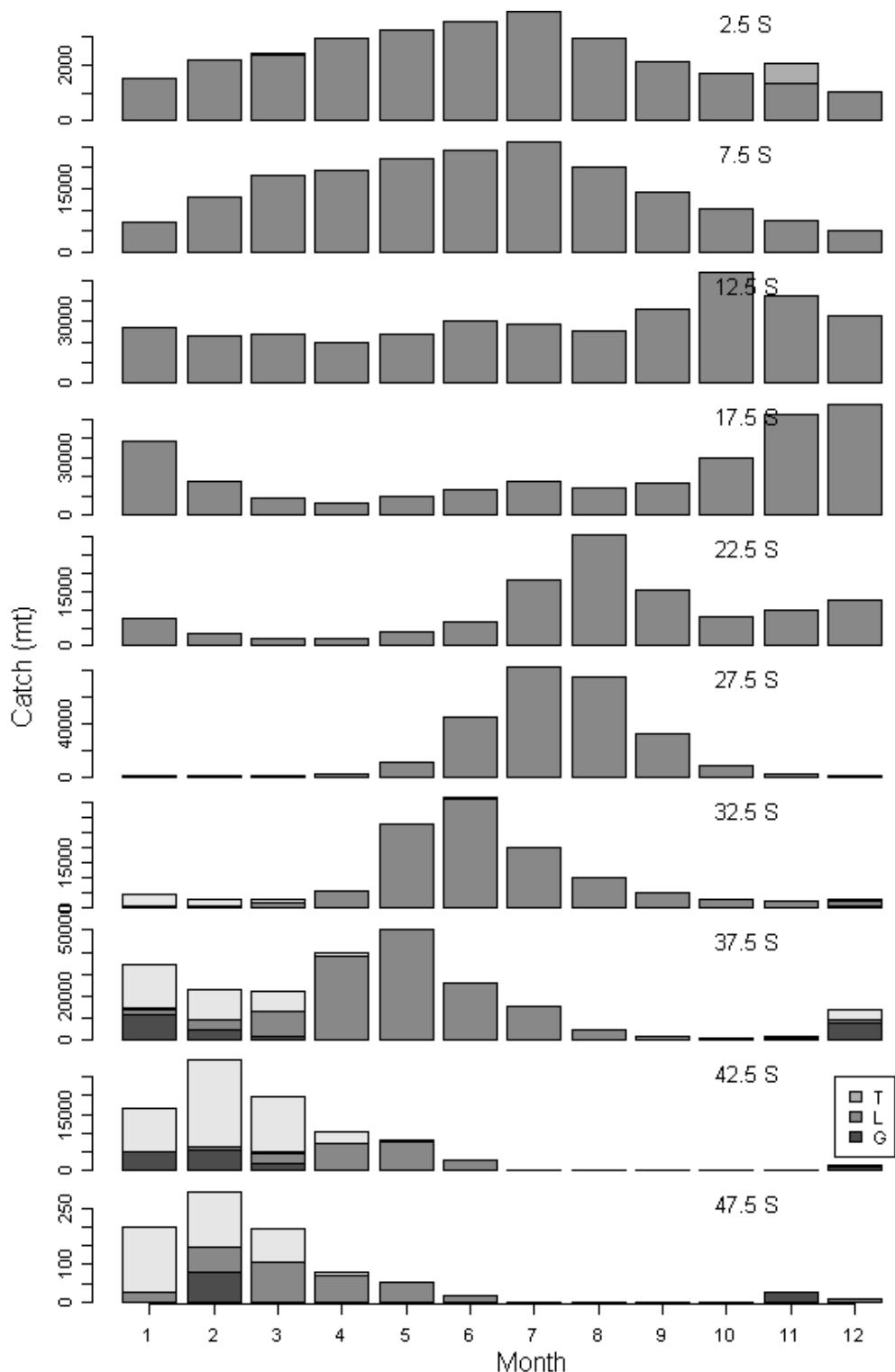
Figure 3: Cumulative monthly distribution of south Pacific albacore catch by gear (T, troll; L, longline; G, drift net) by 5 degree latitudinal band for 1980 to 2003 combined.
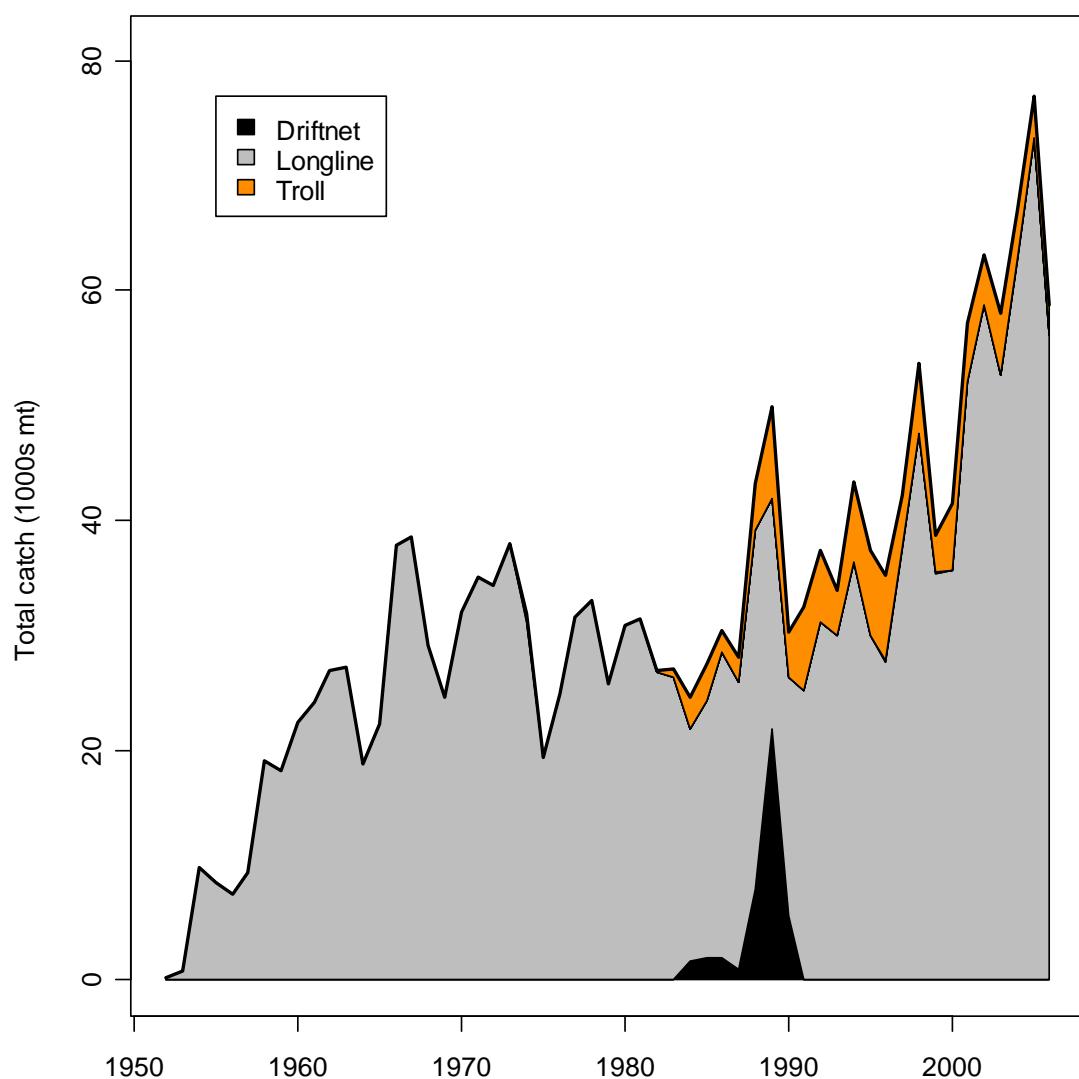
Figure 4: Total annual catch (mt) of south Pacific albacore by fishing method for 1952 to 2006.
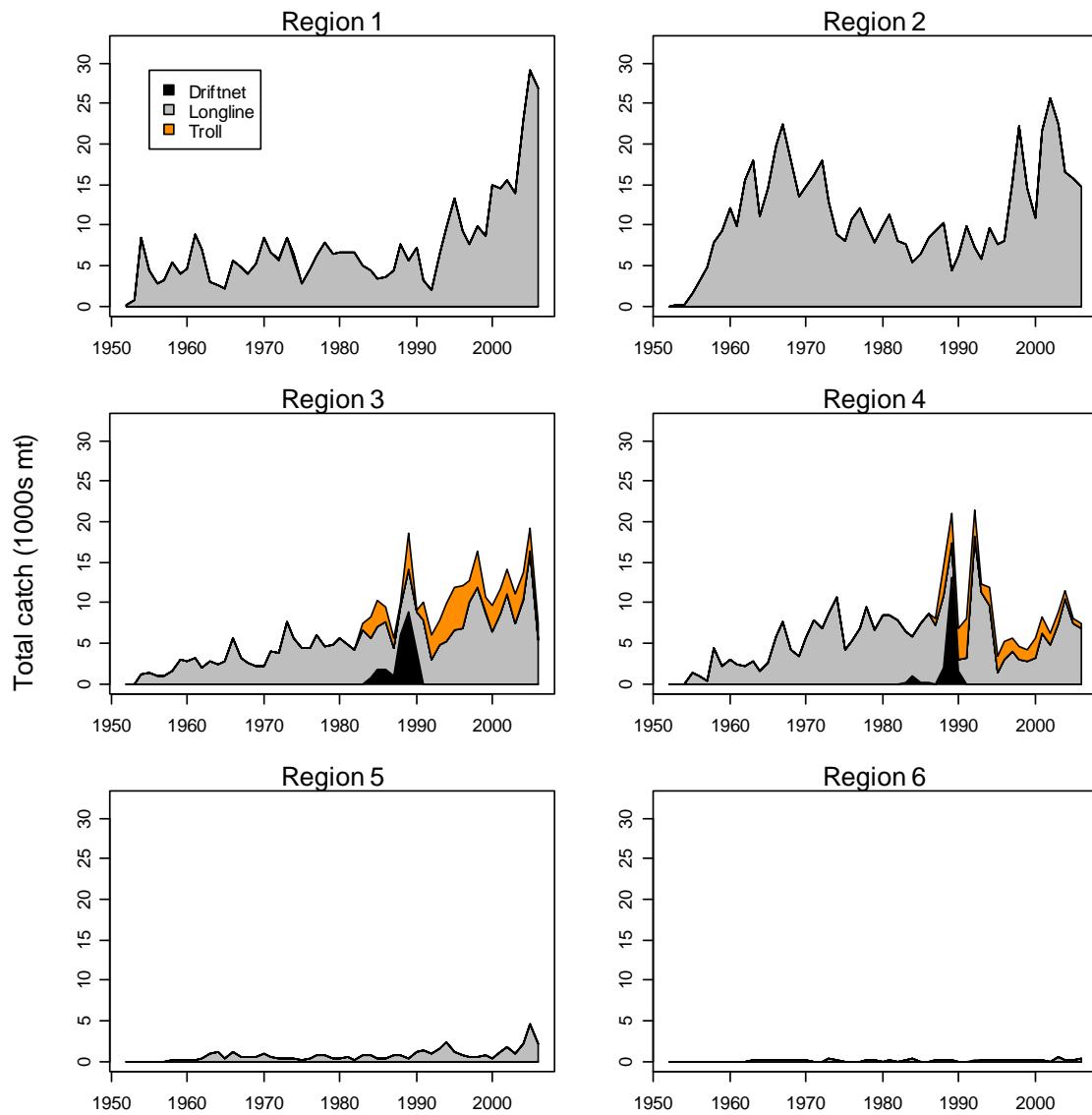
Figure 5: Annual catch (mt) of south Pacific albacore by fishing method and region for 1952 to 2006.
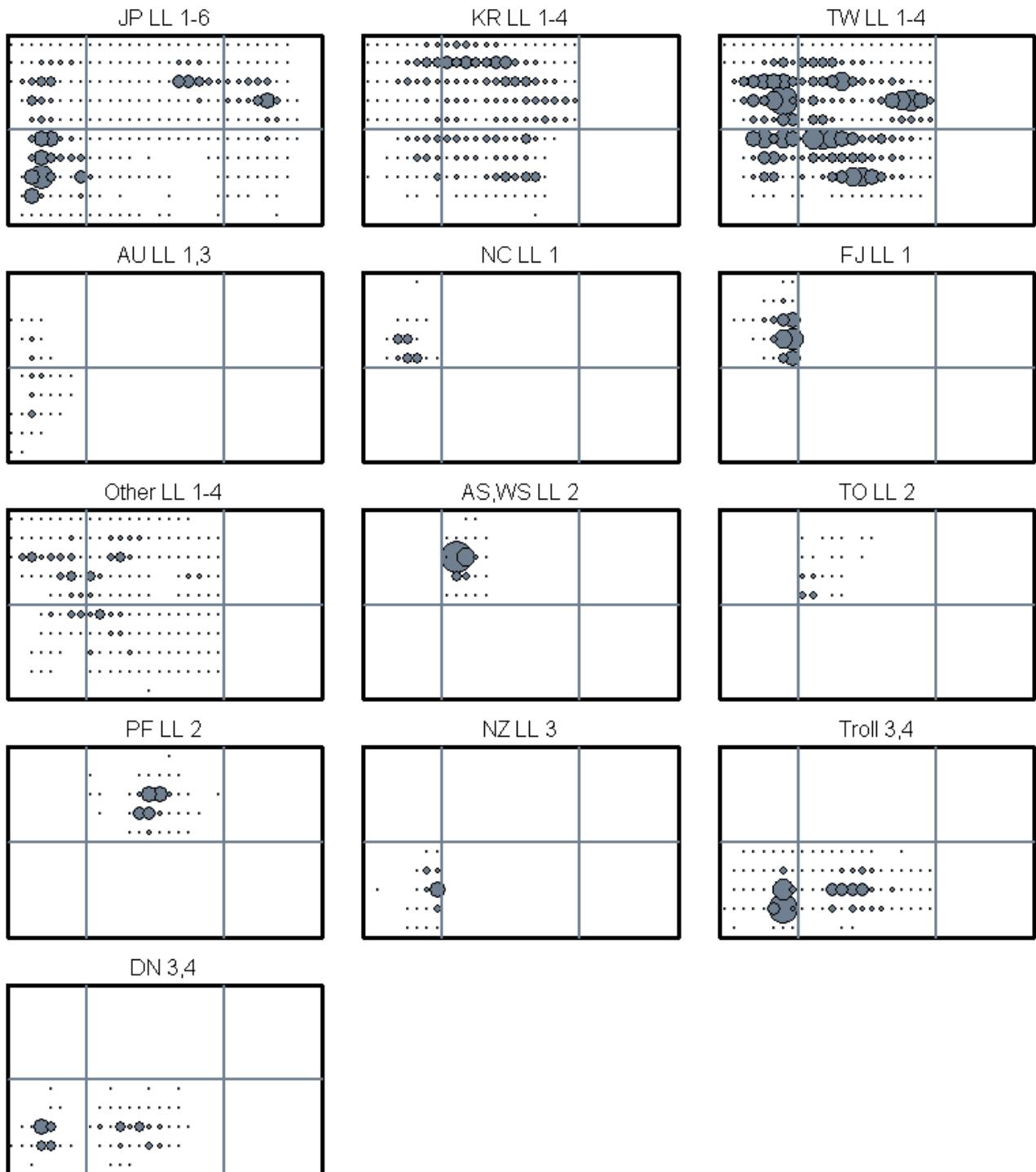
Figure 6: Cumulative albacore catch by fishery by 5 degree square of latitude and longitude from 1970–2006. The circle size is proportional to the cumulative catch (maximum circle size corresponds to 36,000 mt). The grey lines represent the region boundaries.
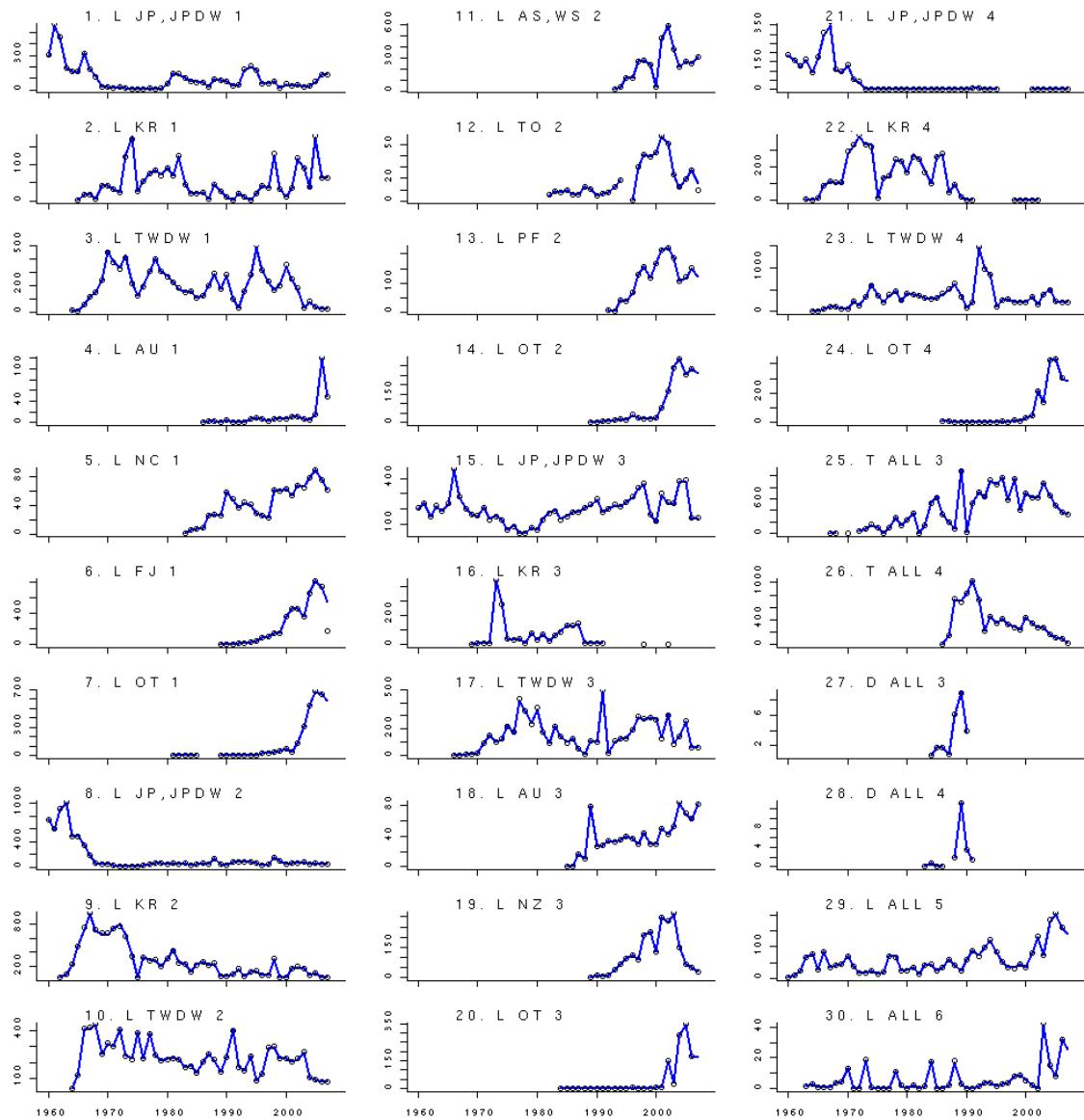
Figure 7: Annual catches (observed) by fishery (catches in thousands of fish for all fisheries except driftnet).
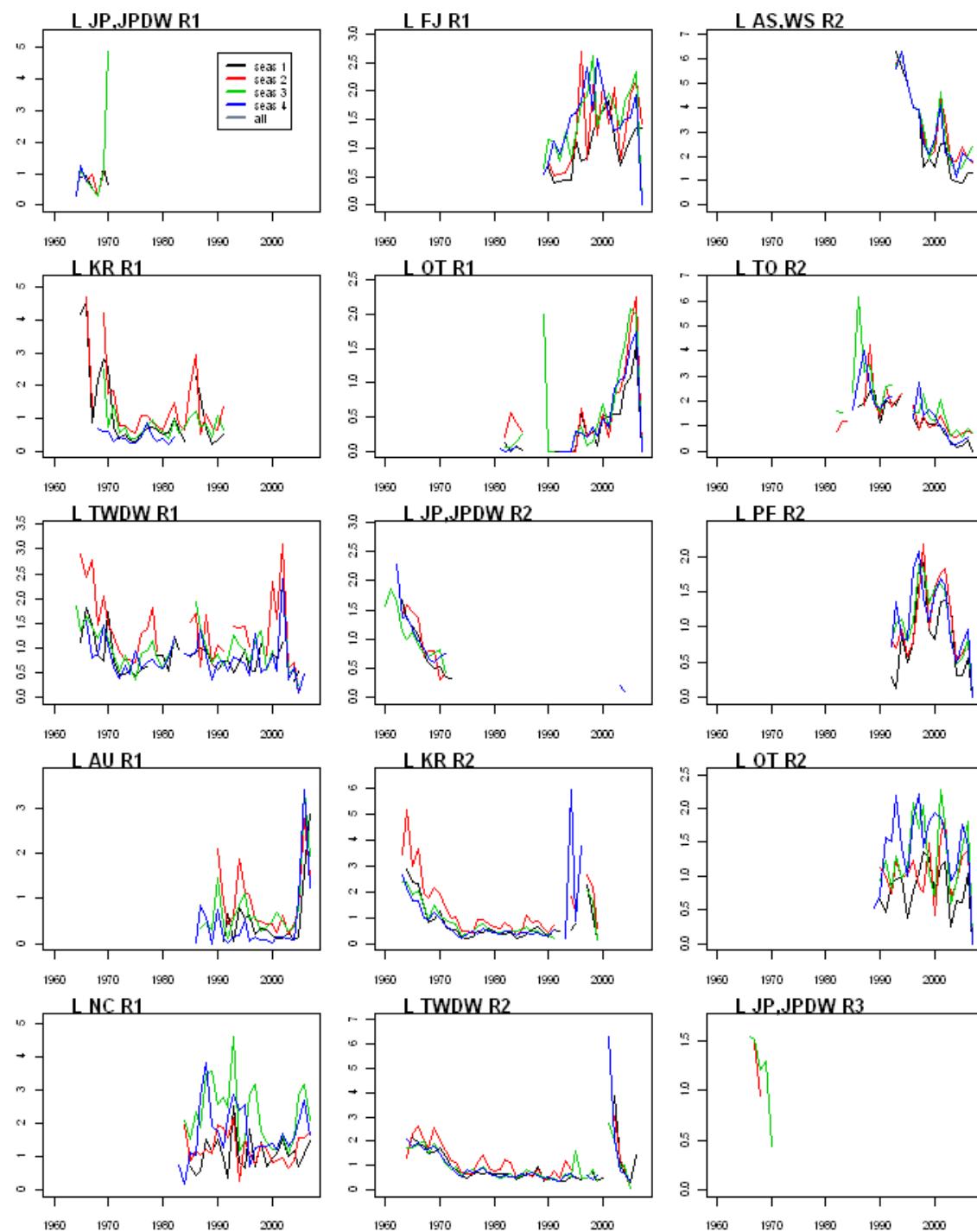
Figure 8a: Annual average catch rates by fishery. Catch rates for standardized fisheries have no units. For non-standardized longline fisheries they are expressed as number per 100 hooks; troll, number per vessel day fished; drift net, mt per day.
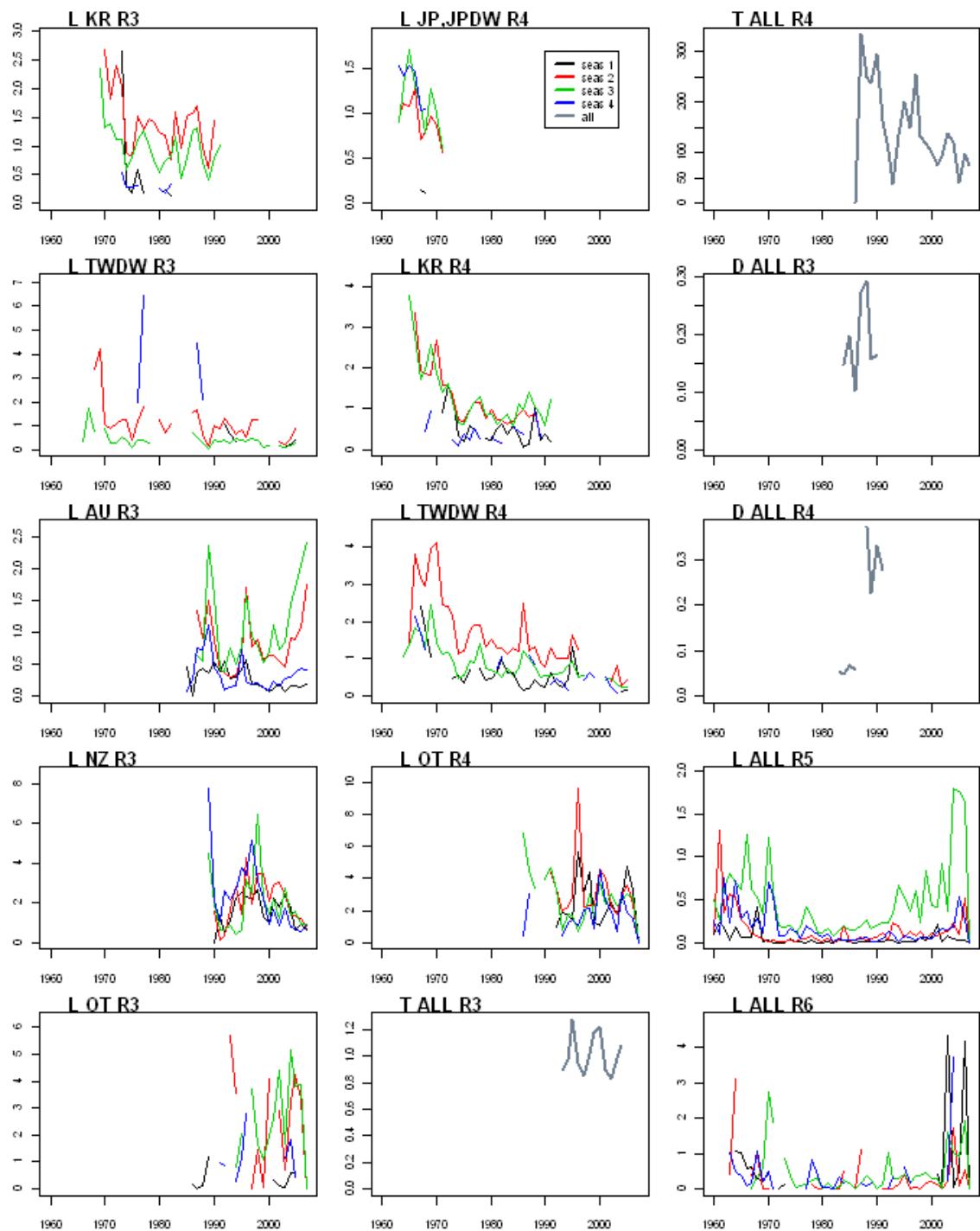
Figure 8b: Annual average catch rates by fishery. Catch rates for standardized fisheries have no units. For non-standardized longline fisheries they are expressed as number per 100 hooks; troll, number per vessel day fished; drift net, mt per day.
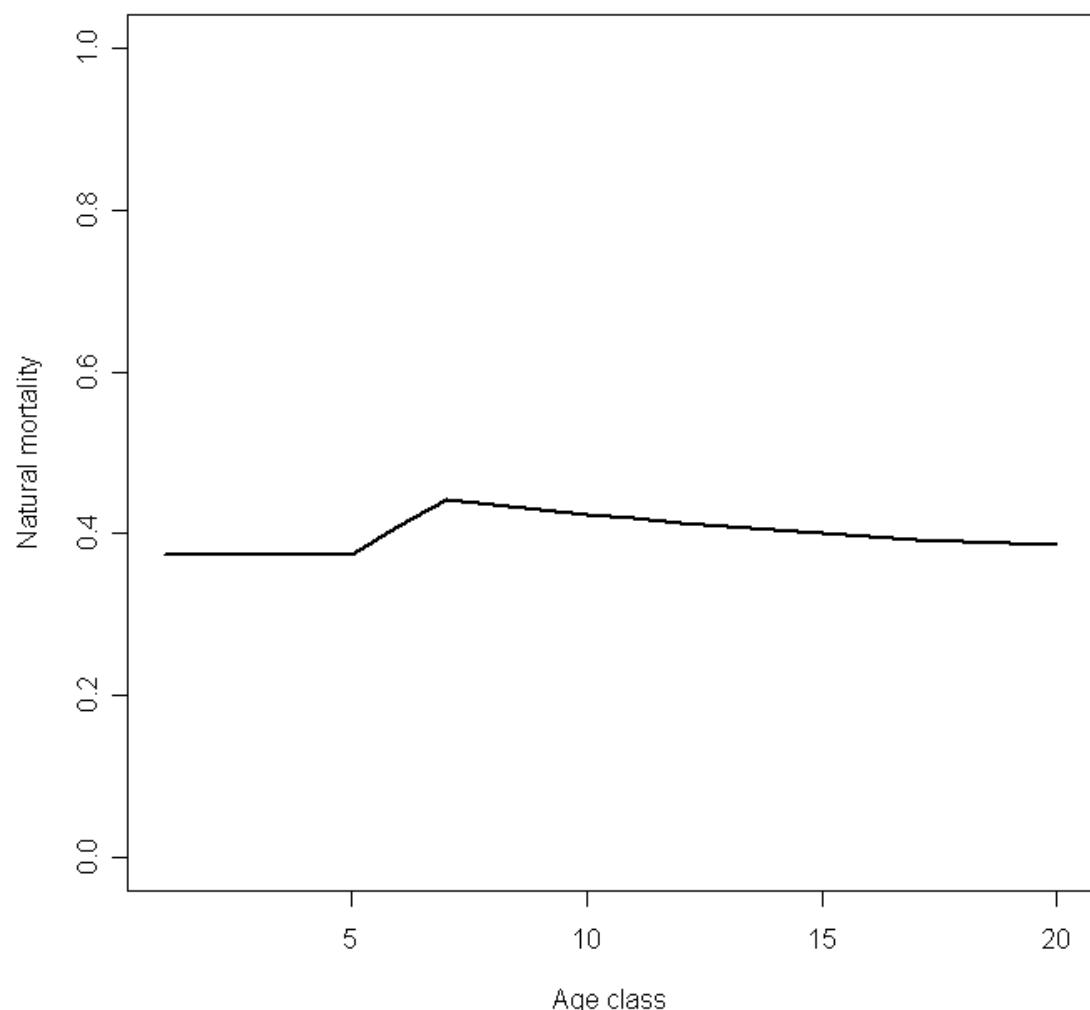
Figure 9: Natural mortality at age
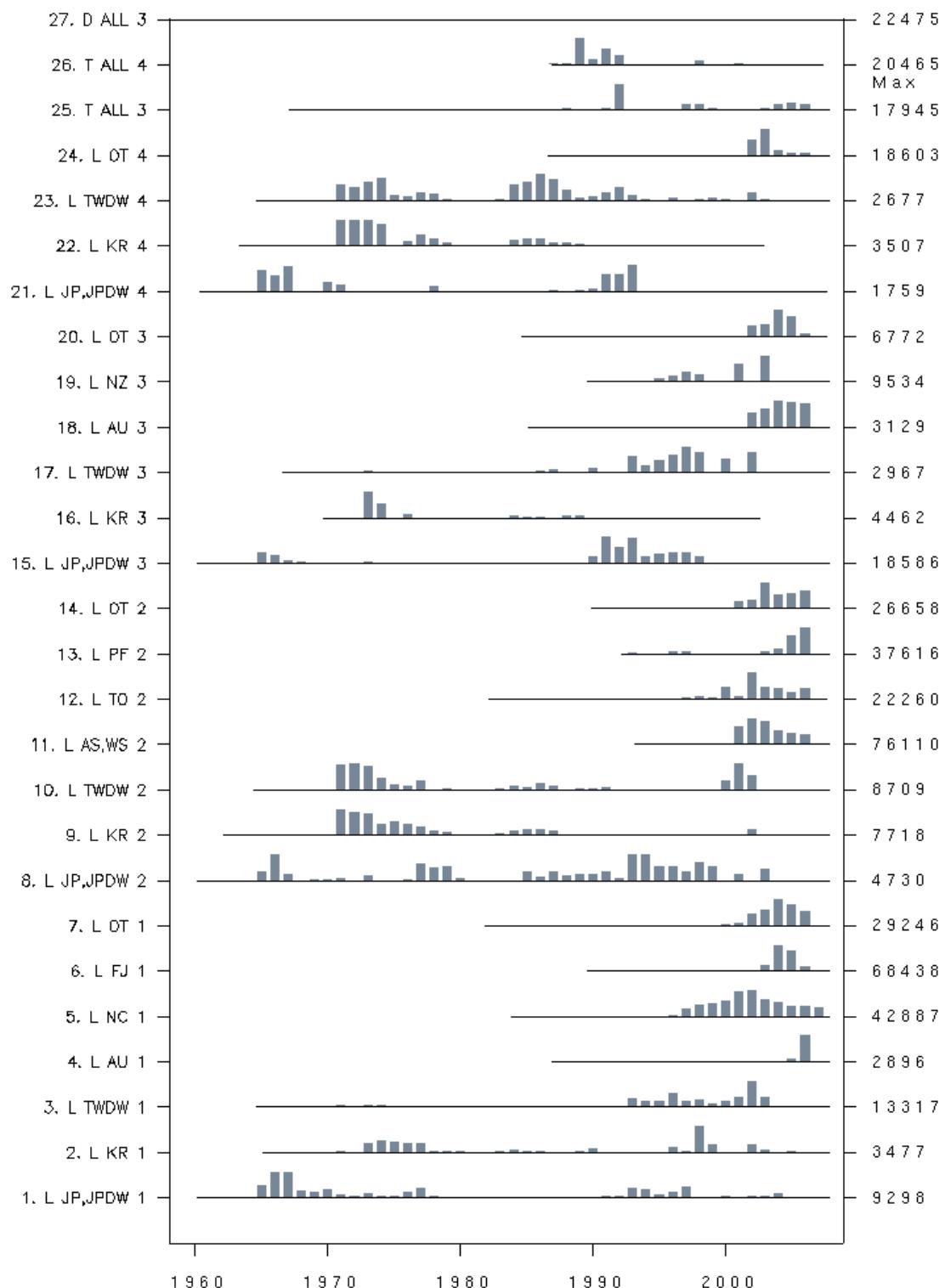
Figure 10: Length frequency samples by fishery and year. The number on the y-axis represents the maximum number of fish measured in a single year for the fishery. The frequency histograms are scaled relative to the maximum value for the fishery. The length of the x-axis denotes the period of catch and effort data from the fishery. No size frequency data were available before 1960.
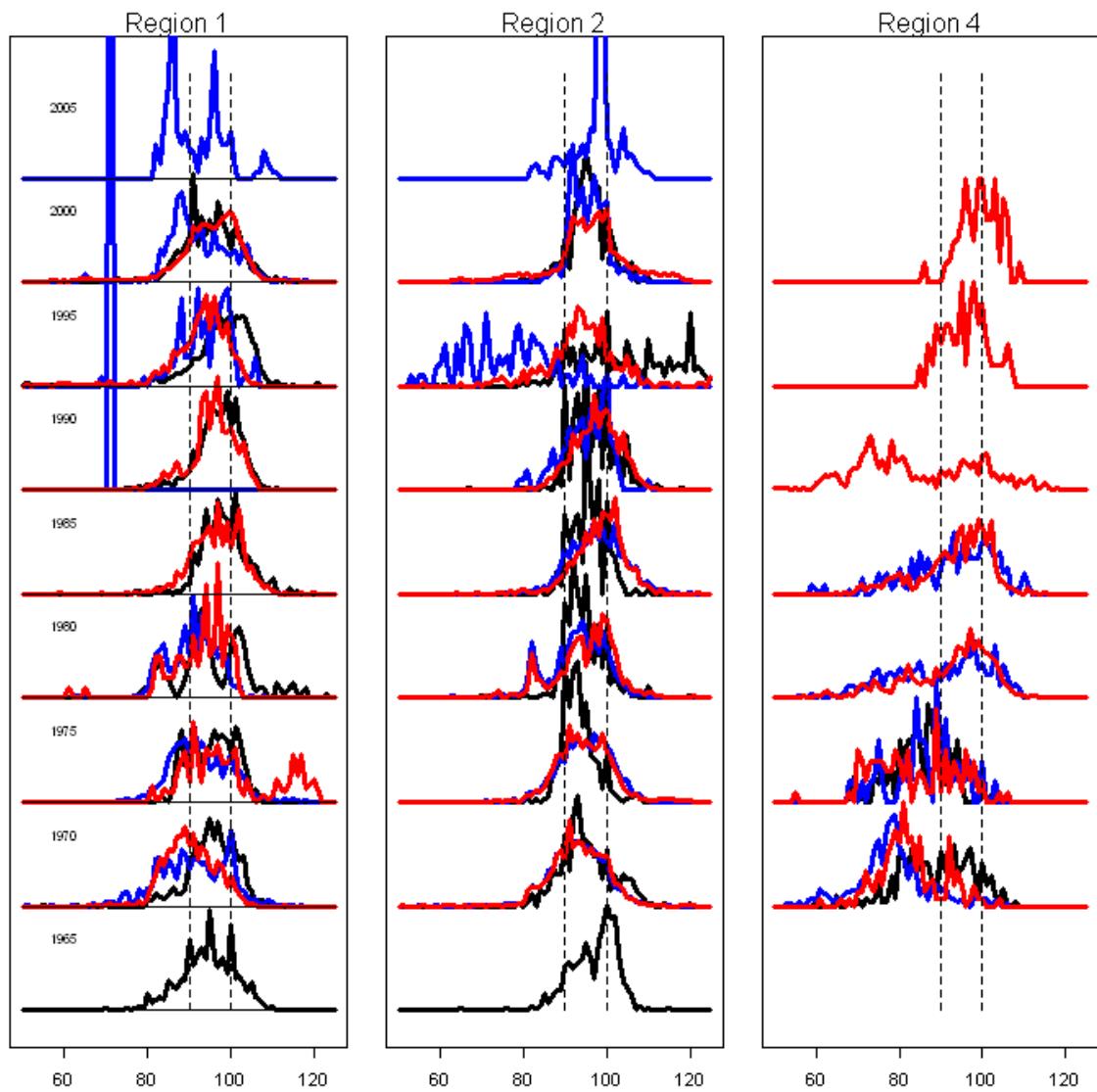
Figure 11a: Five yearly (summer) aggregated length frequency distributions (fork length) of albacore from the Japanese (black), Korean (blue) and Chinese Taipei (red) longline in regions 1, 2, and 4 (insufficient data were available from region 3). The year denotes the first year of the five-year period. The two dashed vertical lines are at 90 and 100 cm.
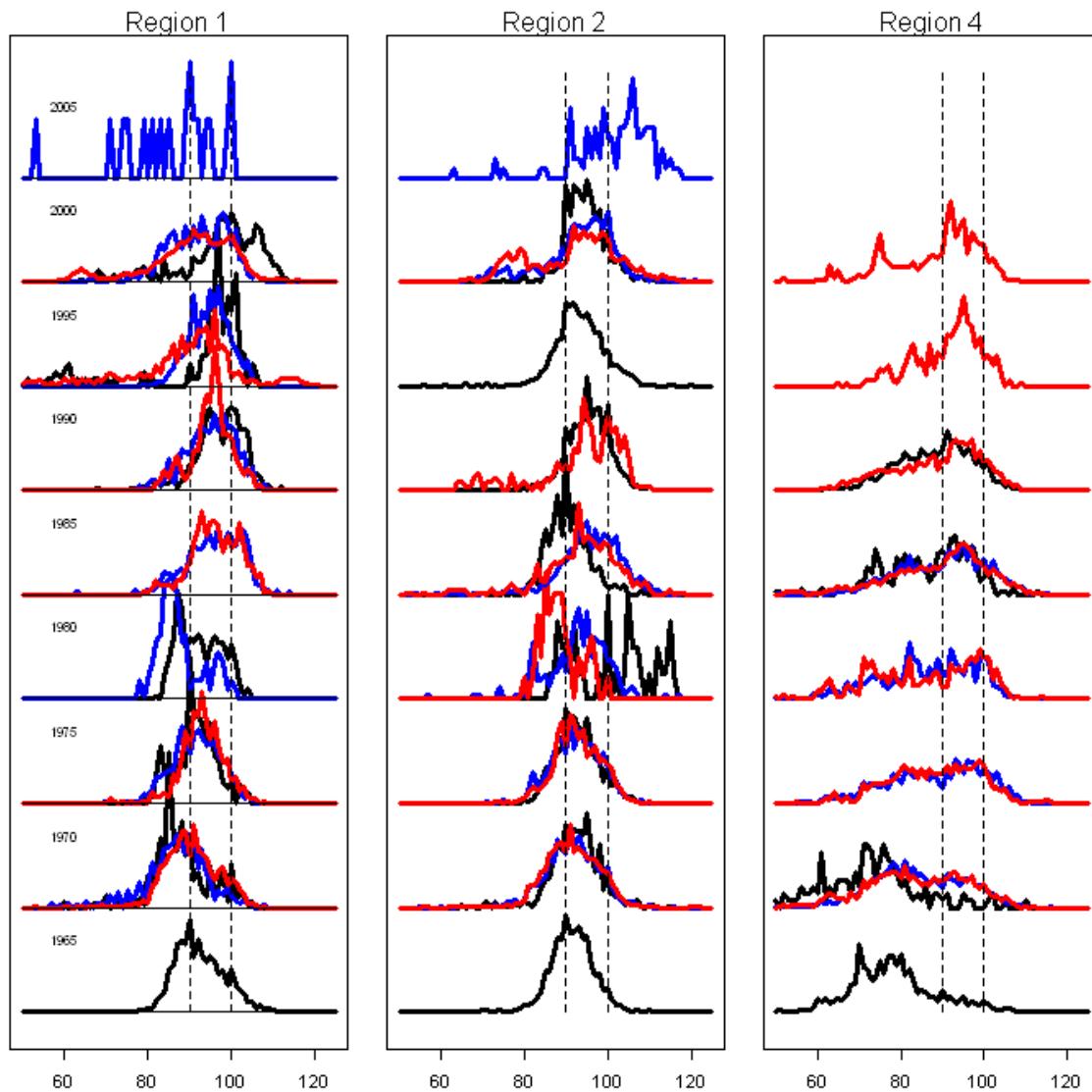
Figure 11b: Five yearly (autumn / fall) aggregated length frequency distributions (fork length) of albacore from the Japanese (black), Korean (blue) and Chinese Taipei (red) longline in regions 1, 2, and 4 (insufficient data were available from region 3). The year denotes the first year of the five-year period. The two dashed vertical lines are at 90 and 100 cm.
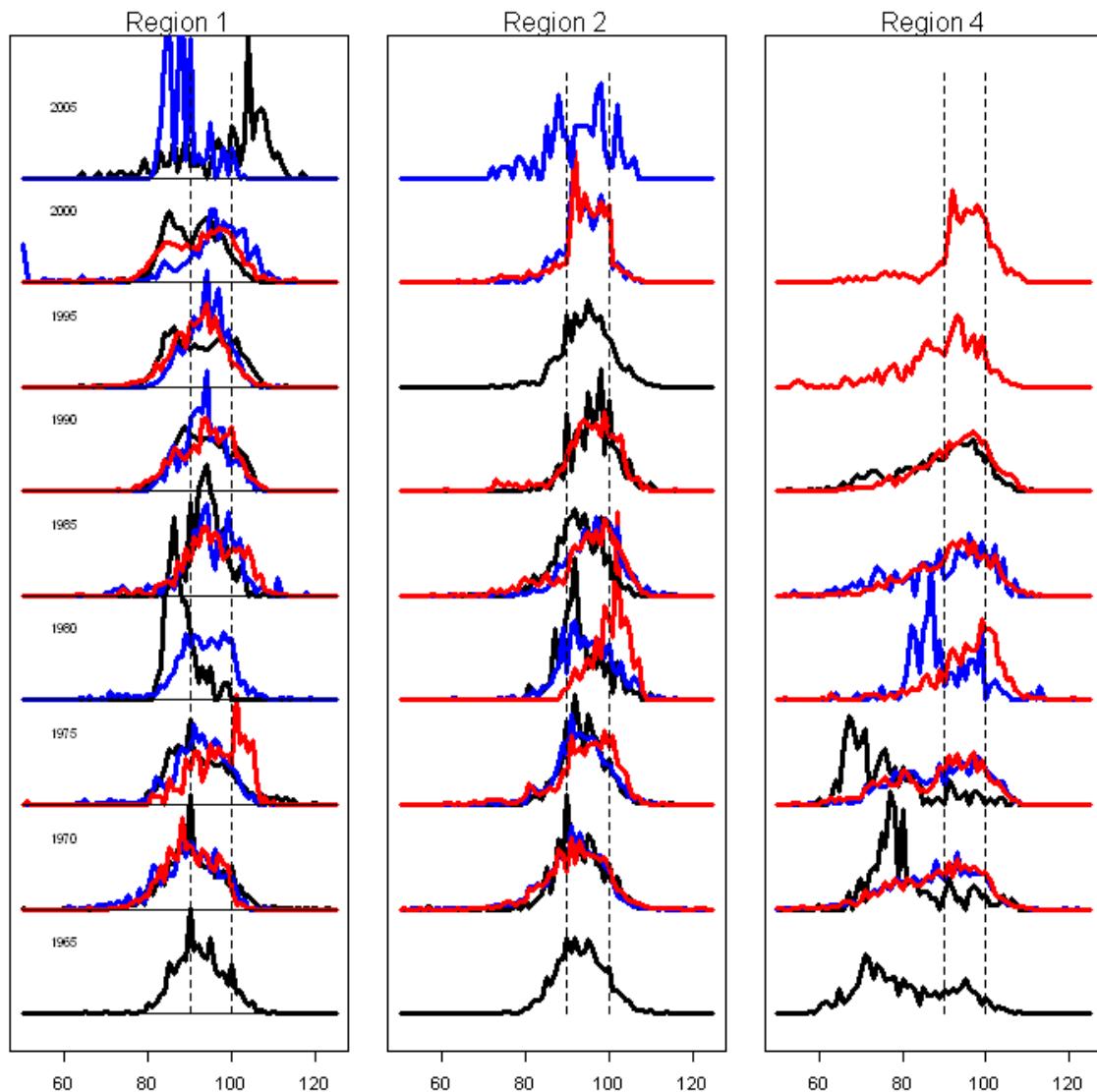
Figure 11c: Five yearly (winter) aggregated length frequency distributions (fork length) of albacore from the Japanese (black), Korean (blue) and Chinese Taipei (red) longline in regions 1, 2, and 4 (insufficient data were available from region 3). The year denotes the first year of the five-year period. The two dashed vertical lines are at 90 and 100 cm.
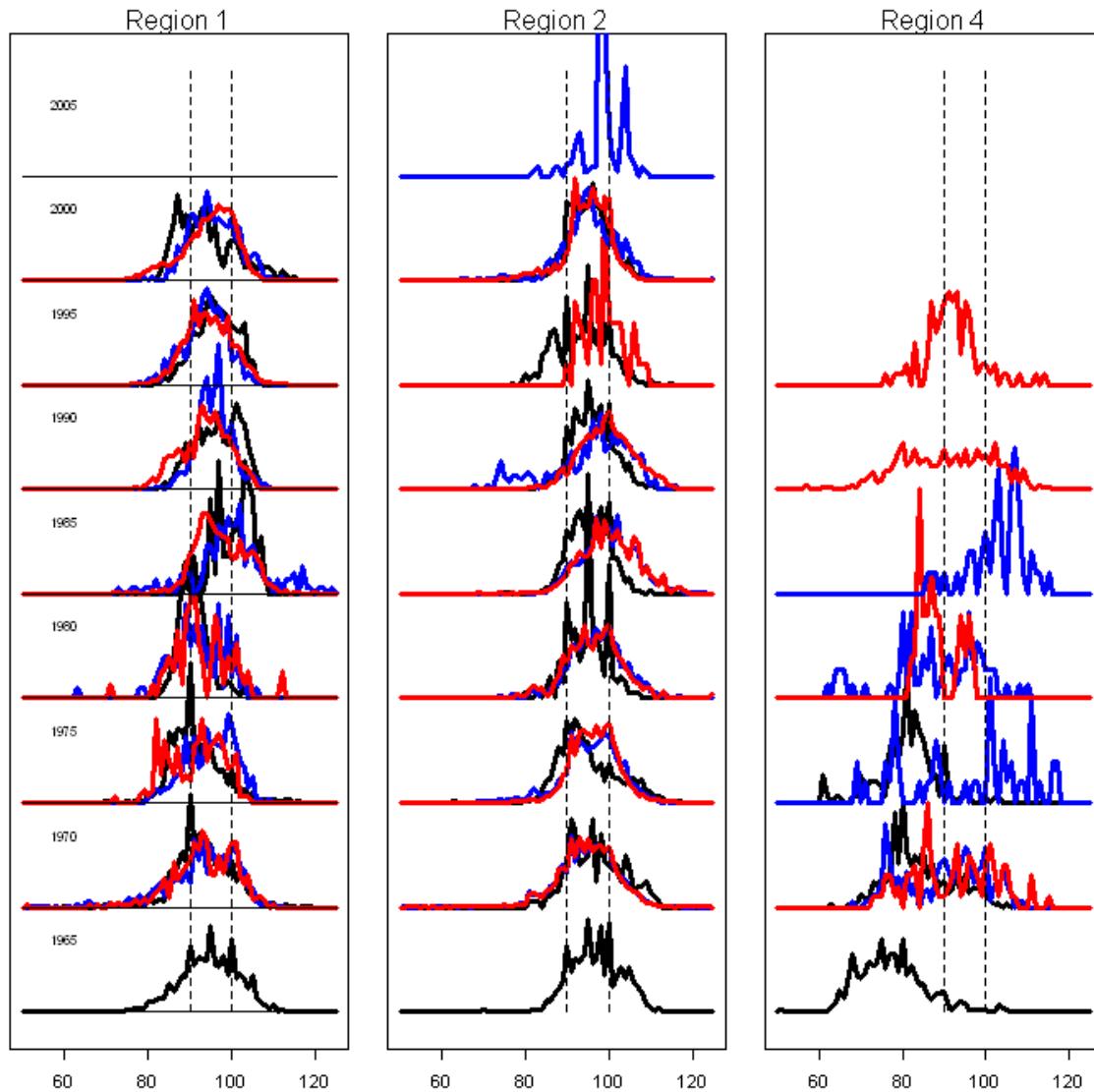
Figure 11d: Five yearly (spring) aggregated length frequency distributions (fork length) of albacore from the Japanese (black), Korean (blue) and Chinese Taipei (red) longline in regions 1, 2, and 4 (insufficient data were available from region 3). The year denotes the first year of the five-year period. The two dashed vertical lines are at 90 and 100 cm.
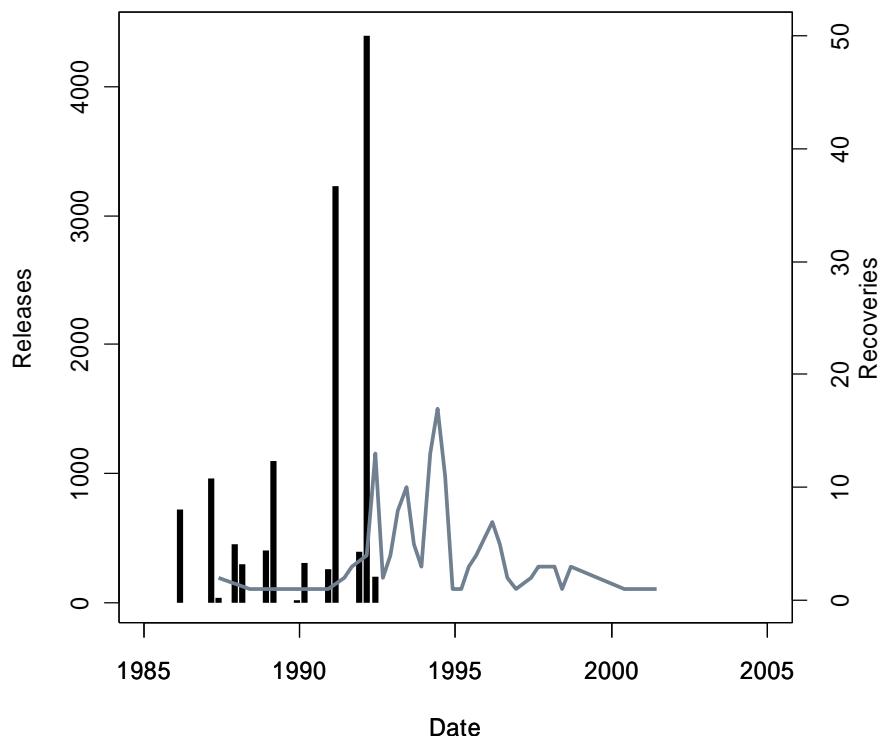
Figure 12: Tag releases (bars) and recoveries (line) by quarter for the south Pacific albacore fishery.
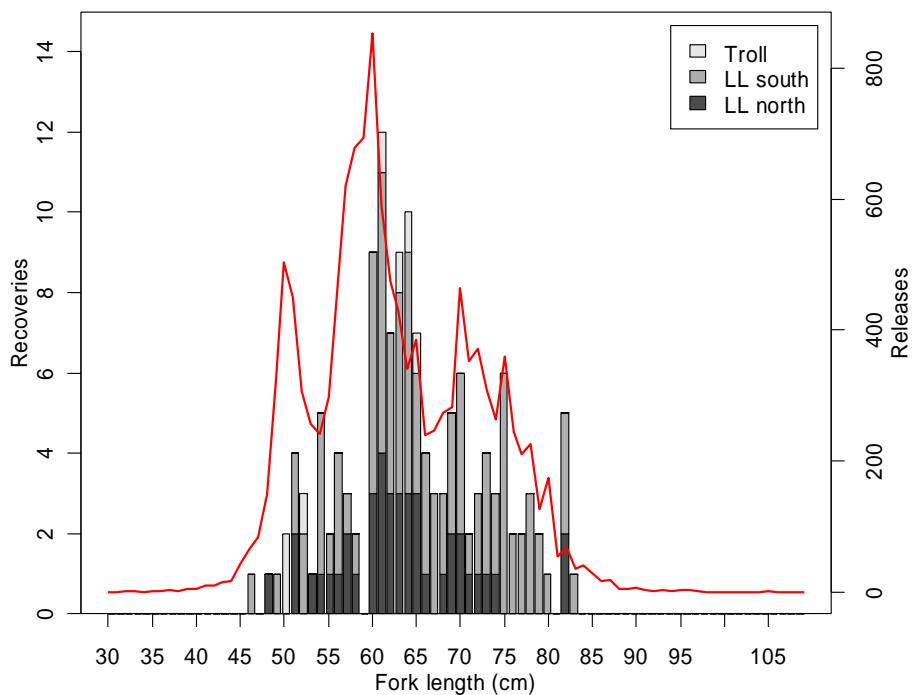
Figure 13: The total number of released tagged albacore (red line) and the number of recoveries (bar plot) by length class. The recoveries are aggregated by groups of fisheries; northern and southern longline fisheries and the troll fisheries.
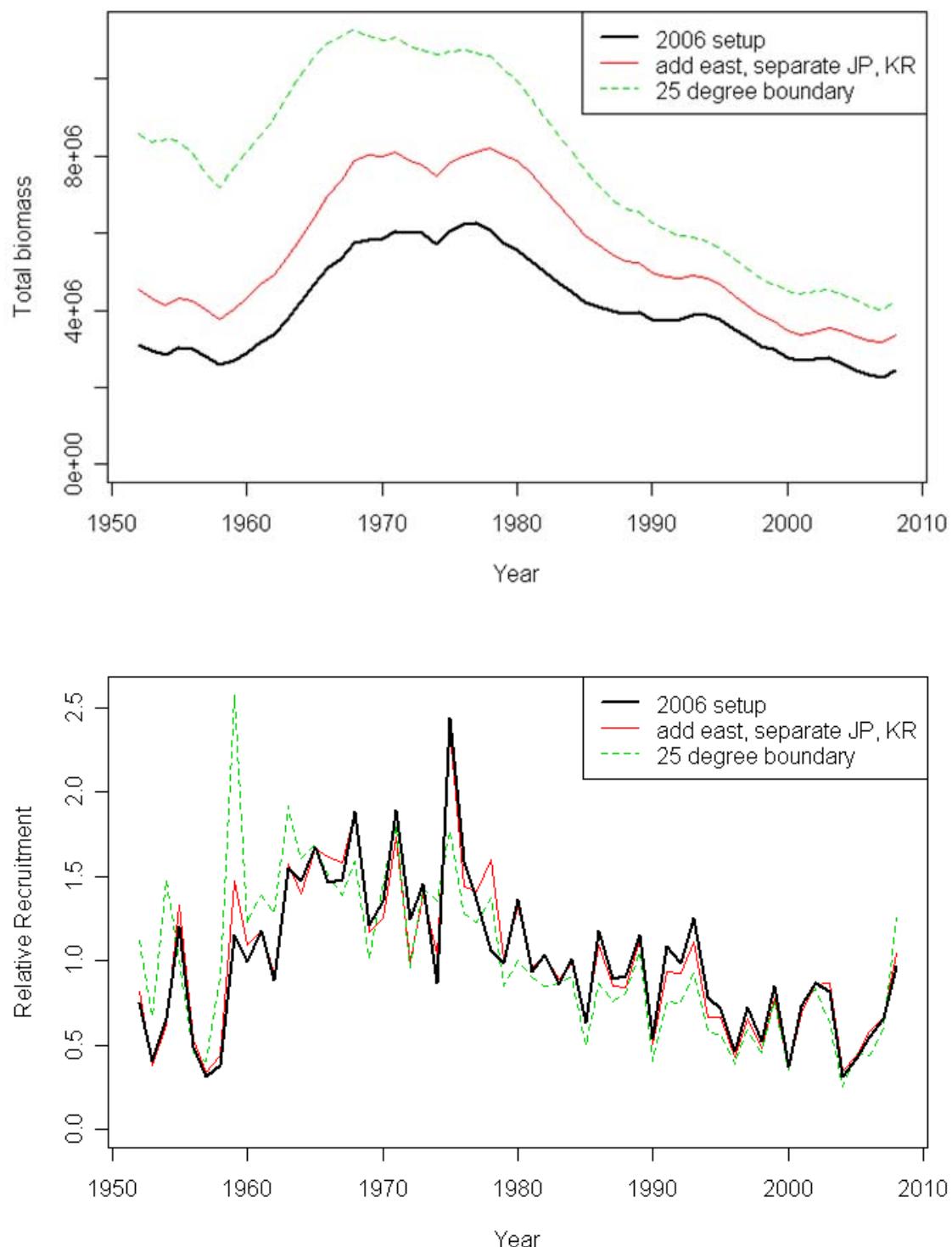
Figure 14: Structural comparison 1: Annual trends in adult biomass and relative recruitment from 3 models: 1) the same setup as in 2006 (2006 setup), 2) model 1 with two regions added to the east, and Japanese and Korean fisheries separated, and 3) model 2 with the boundary shifted from 30S to 25S.
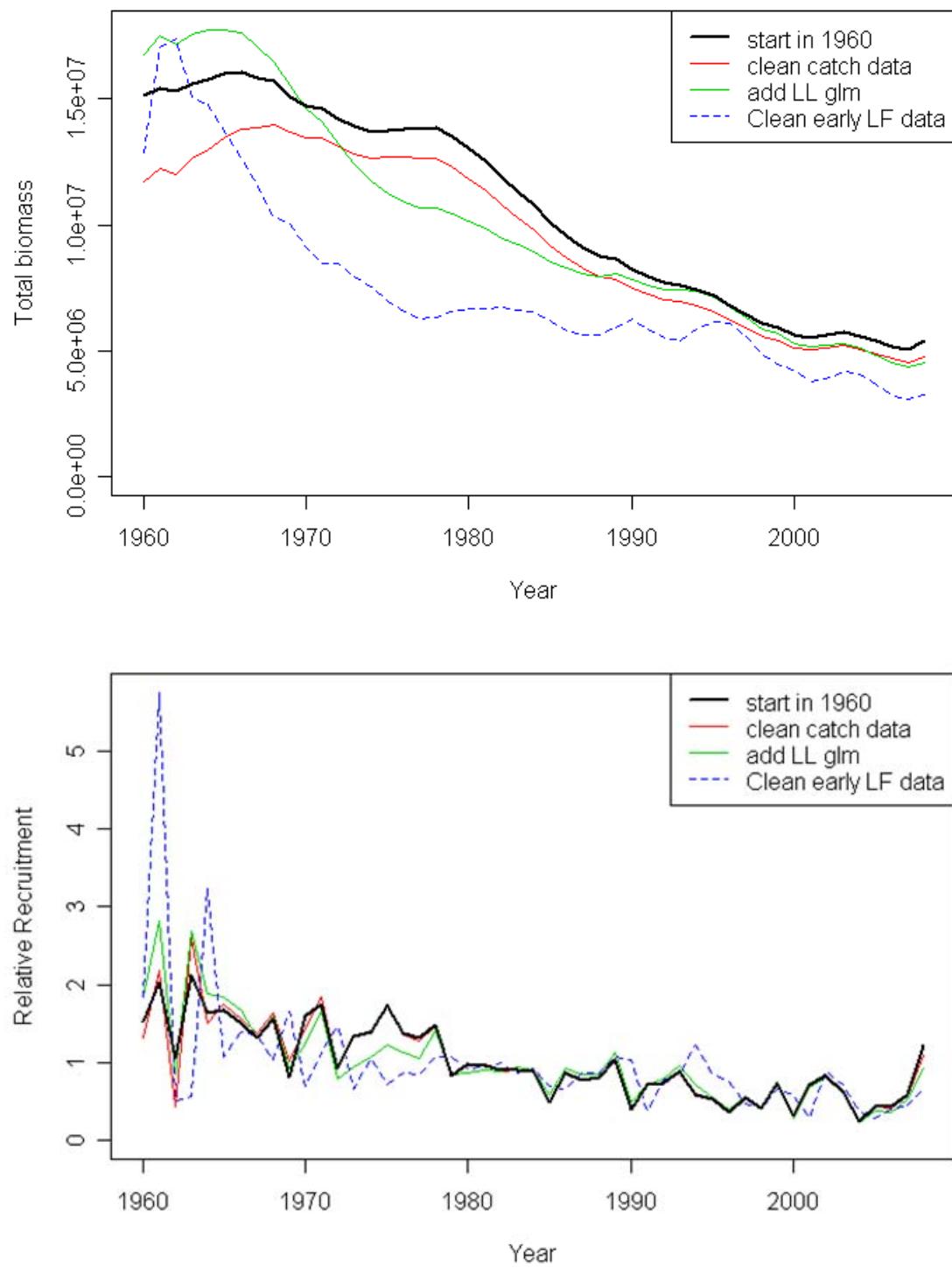
Figure 15: Structural comparison 2: Annual trends in adult biomass and relative recruitment from 4 models: 1) the same setup as in model 3 in the previous figure , but starting in 1960, 2) model 2 with catch data cleaned up, 3) model 2 with longline effort for JP, KR, and TW fisheries replaced based on the standardised CPUE, 4) model 3 without the LF data collected in Pago-Pago before 1971.
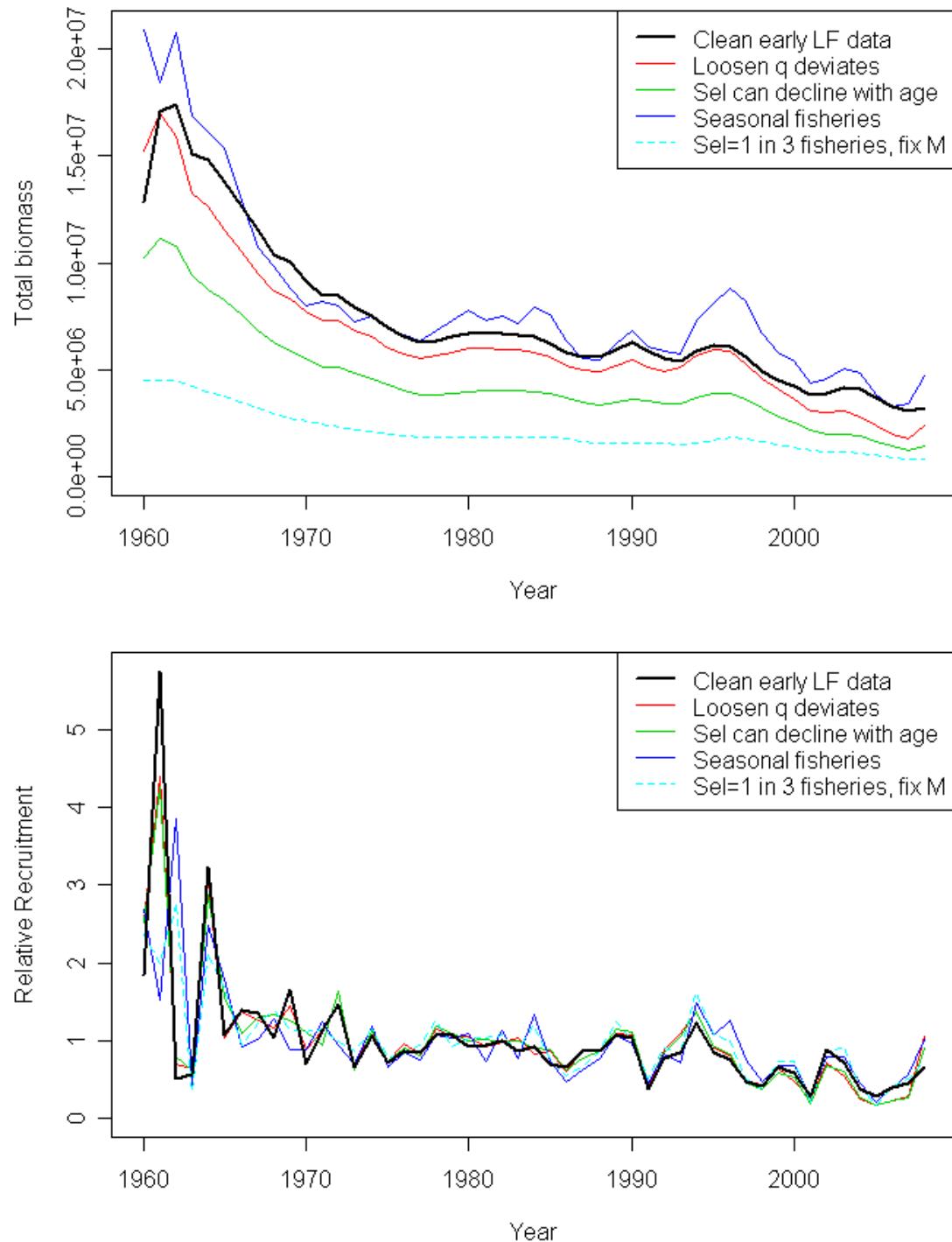
Figure 16: Structural comparison 3: Annual trends in adult biomass and relative recruitment from 5 models: 1) the same setup as in model 4 in the previous figure, 2) model 2 with catchability deviates relaxed for non-standardized fisheries, 3) model 2 with selectivity permitted to decline with increasing age for all longline fisheries except those in region 2, 4) model 3 with seasonal selectivity variation introduced into all longline fisheries, 5) model 4 with selectivity permitted to decline for all fisheries except those 3 fisheries with the largest fish observed, and natural mortality fixed at 0.4.
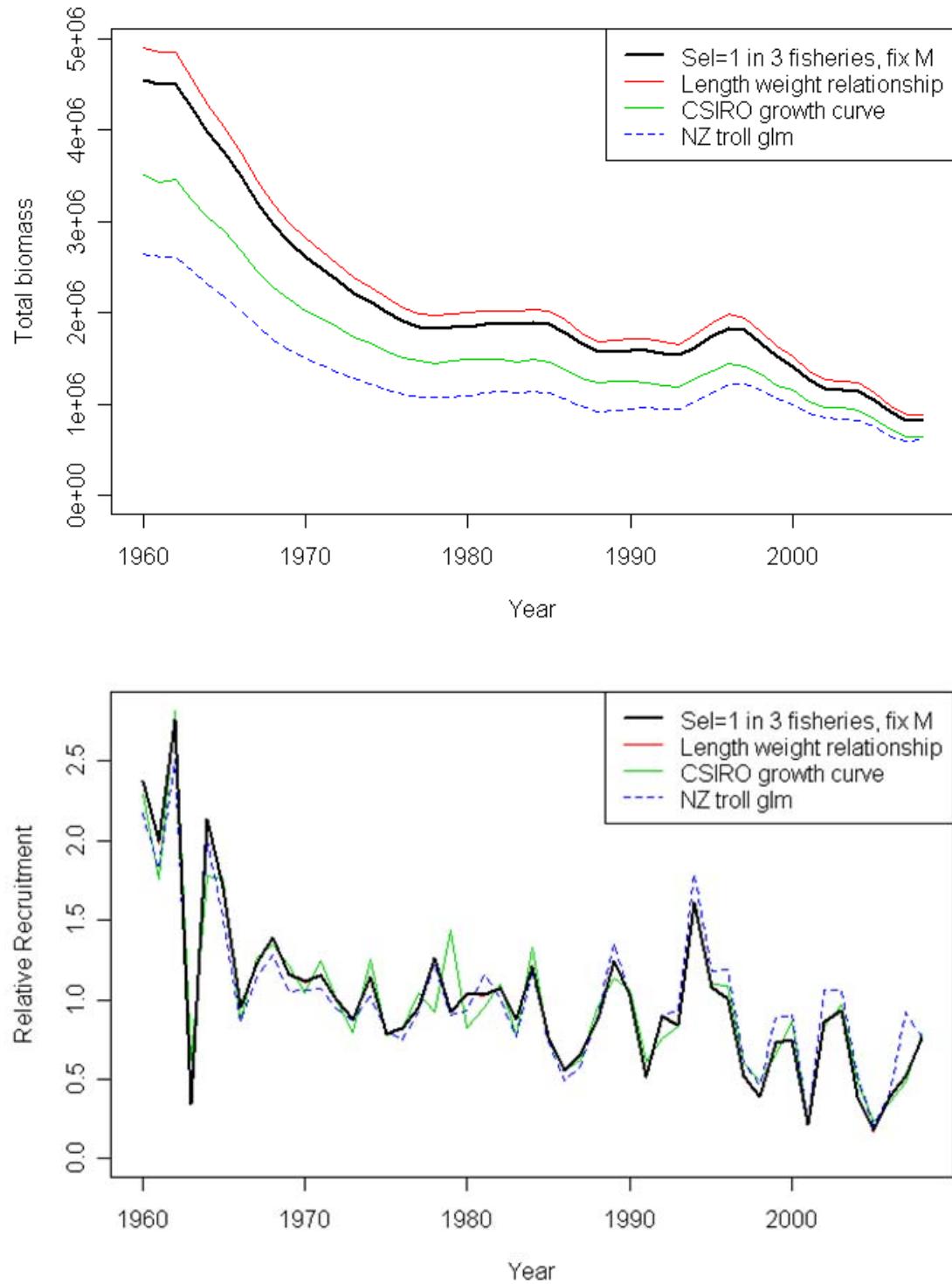
Figure 17: Sensitivity analysis: A comparison of the annual trends in adult biomass and relative recruitment from 4 models: 1) the same setup as in model 5 in the previous figure, 2) model 1 with the Australian length-weight relationship, 3) model 1 with the Australian growth curve, 4) Model 1 with effort adjusted according to the standardised NZ troll CPUE.
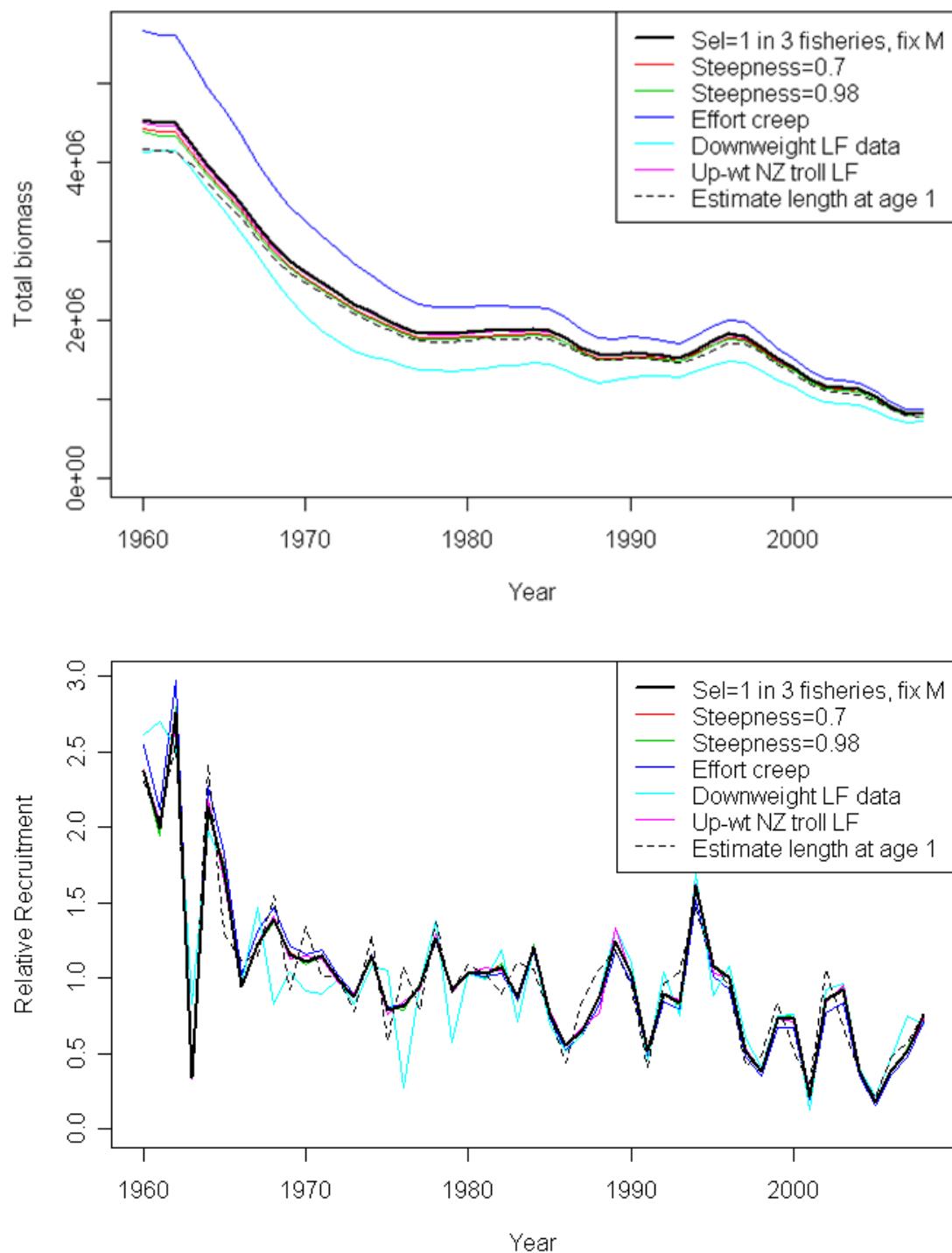
Figure 18: Further sensitivity analyses: A comparison of the annual trends in adult biomass and relative recruitment from 7 models: 1) the same setup as in model 1 in the previous figure, 2) Model 1 with the steepness set to 0.7, 3) model 1 with the steepness set to 0.98, 4) Model 1 with effort creep of 0.5% per year, 5) Model 1 with the effective sample size multiplier for all length frequency data reduced by 50%, 6) Model 1 with the effective sample size multiplier for New Zealand troll length frequency data increased by 100%, 7) Model 1 with length at age 1 estimated.
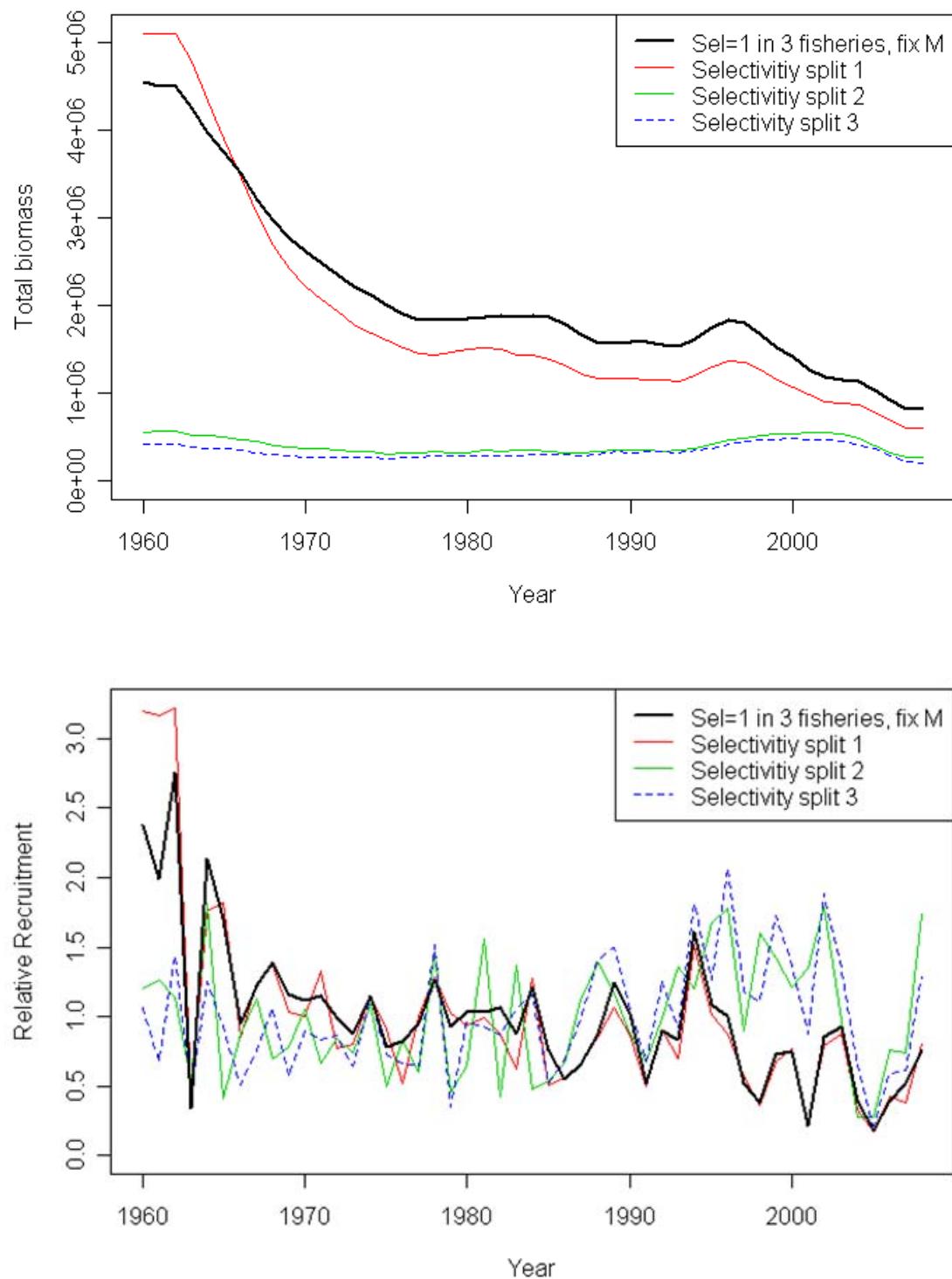
Figure 19: Sensitivity analysis to time varying selectivity
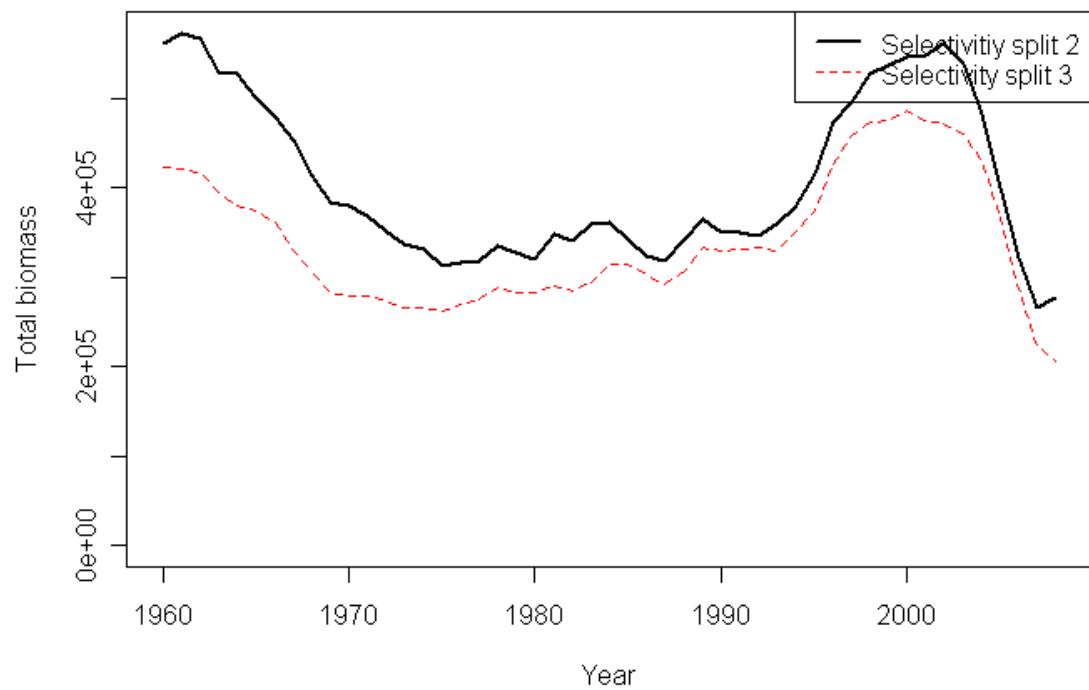
Figure 20: Sensitivity analysis to time varying selectivity 2.
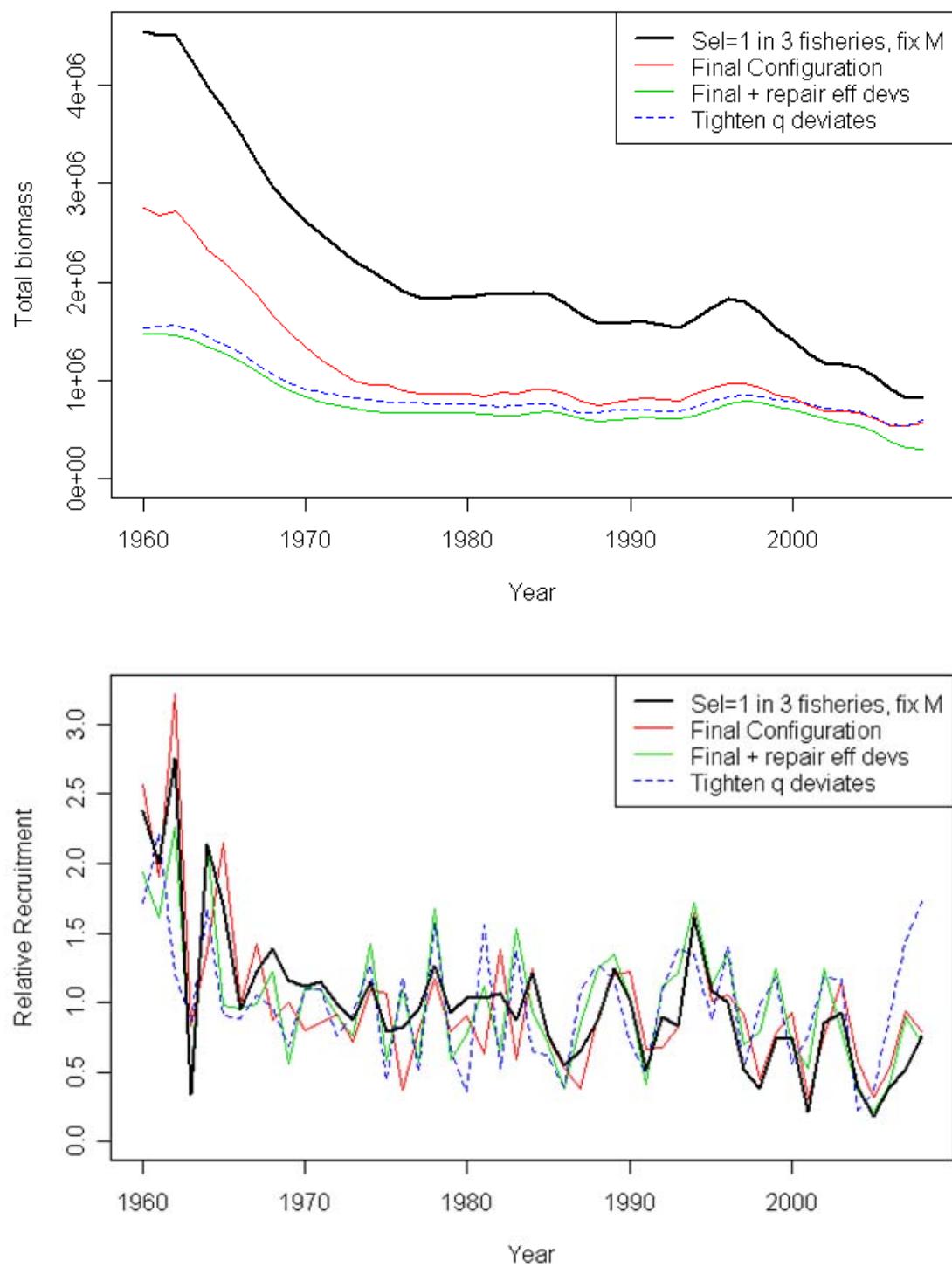
Figure 21: Final runs
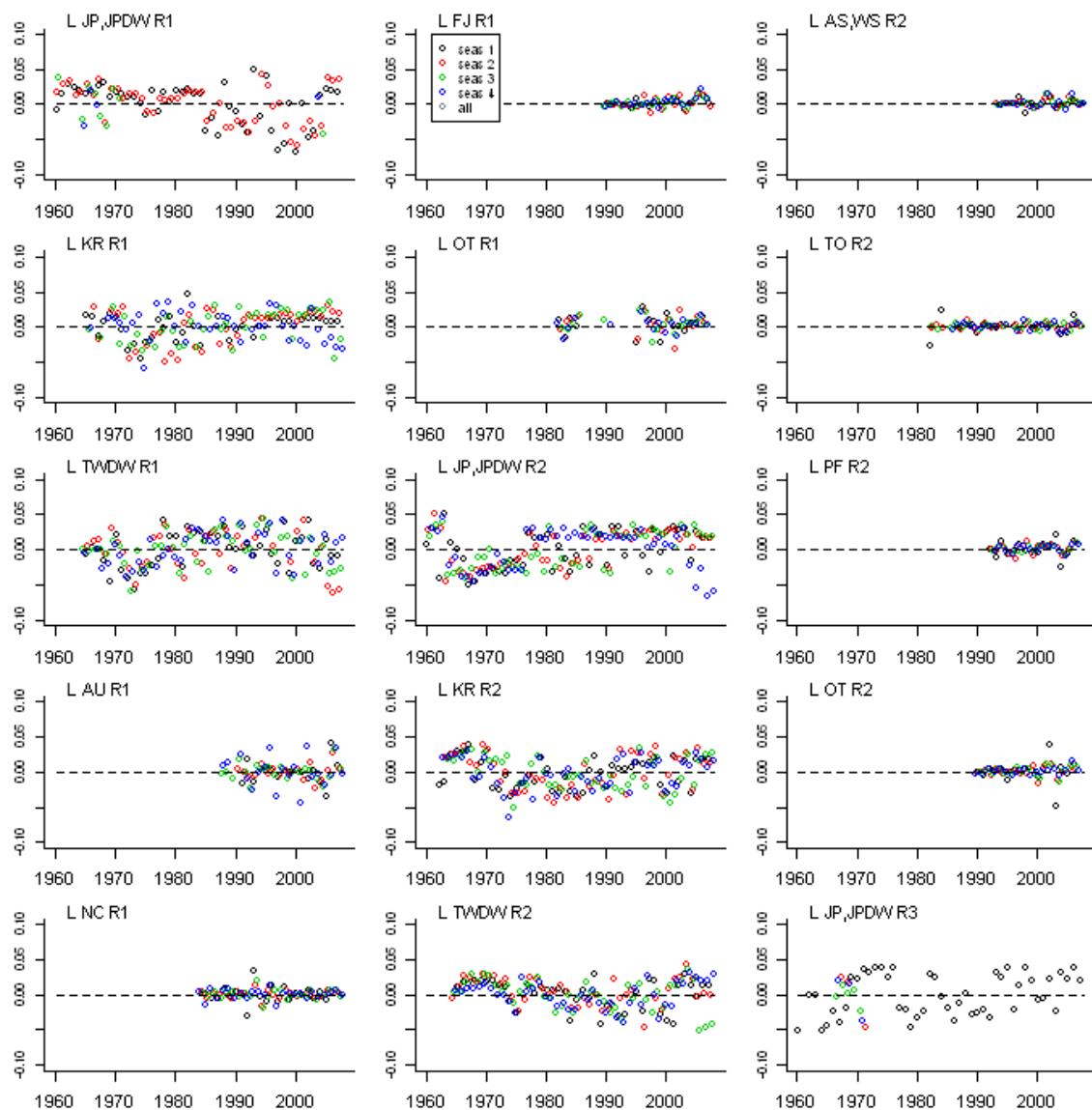
Figure 22a: Residuals of ln (total catch) for each fishery.
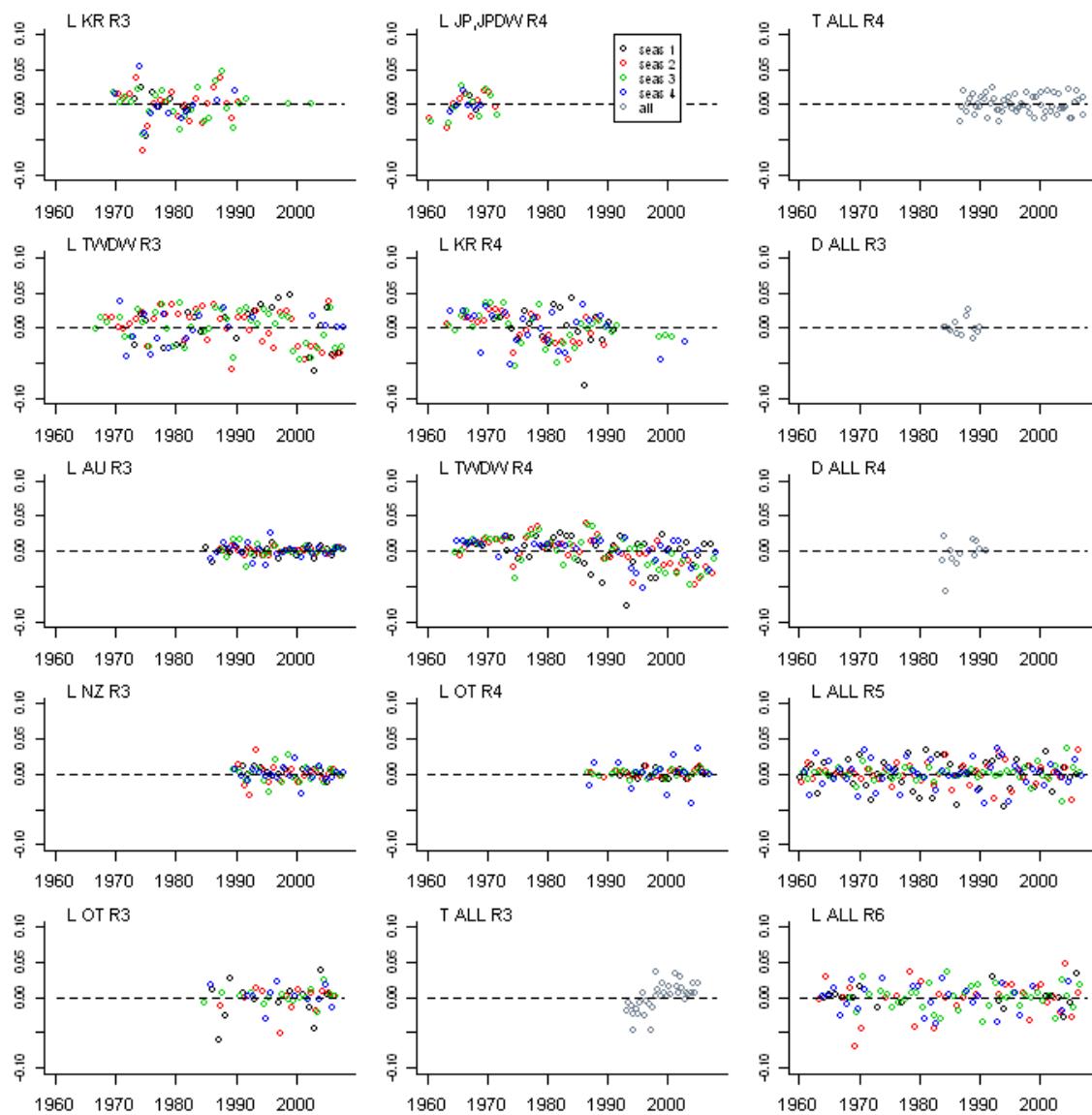
Figure 22b: **Residuals of ln (total catch) for each fishery.**
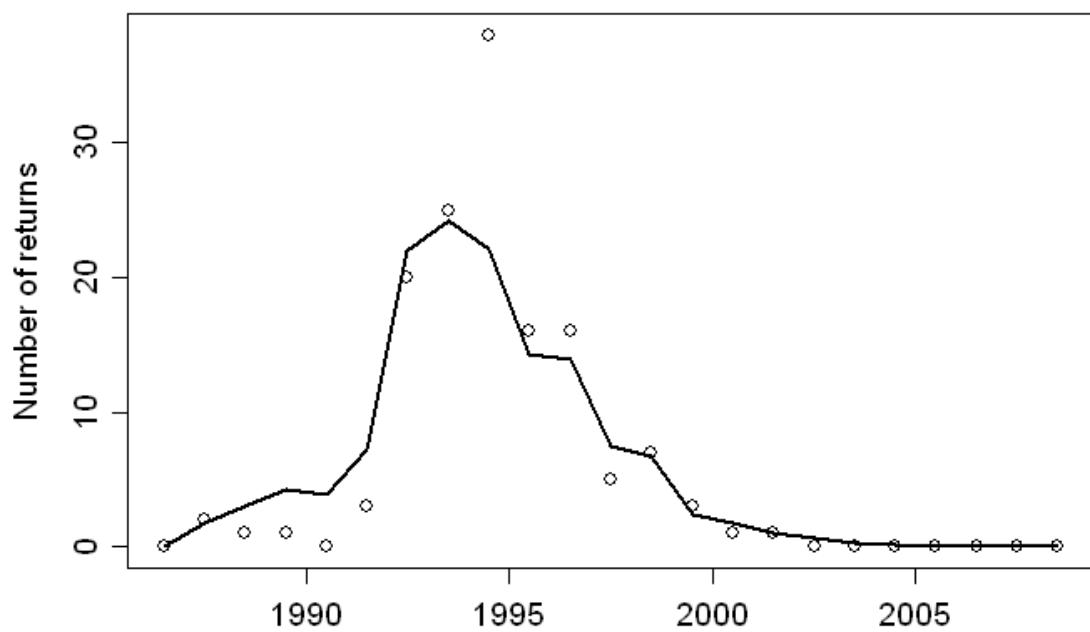
Figure 23: A comparison of observed (points) and predicted (line) number of annual tag returns from the south Pacific albacore fishery.
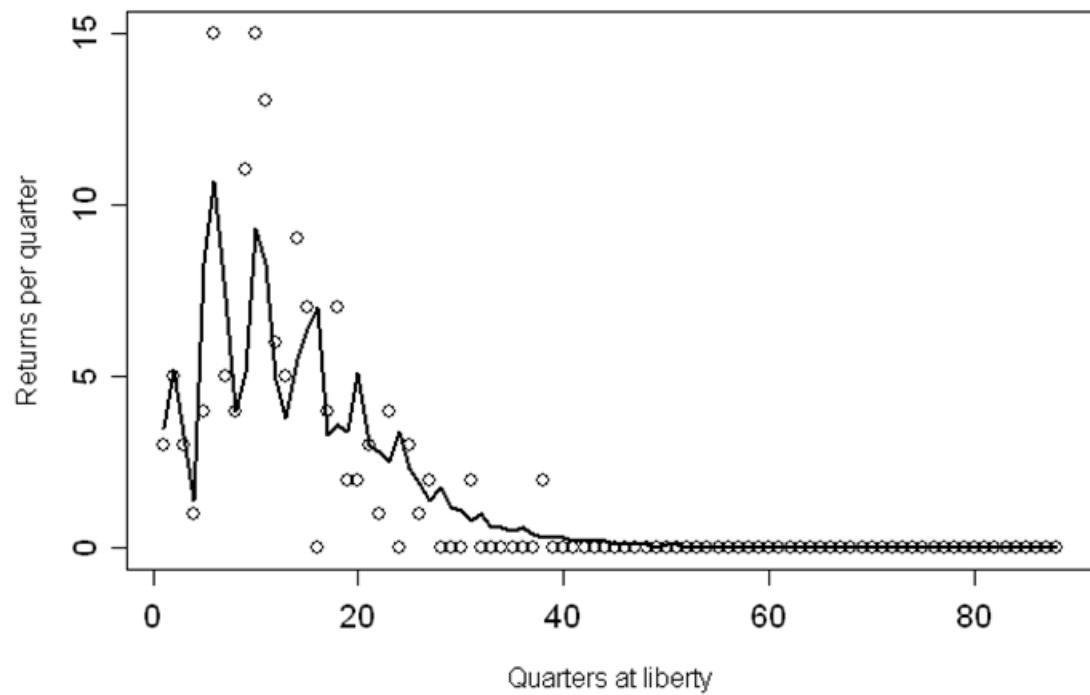
Figure 24: A comparison of observed (points) and predicted (line) number of tag returns by period at liberty (quarters) from the south Pacific albacore fishery.
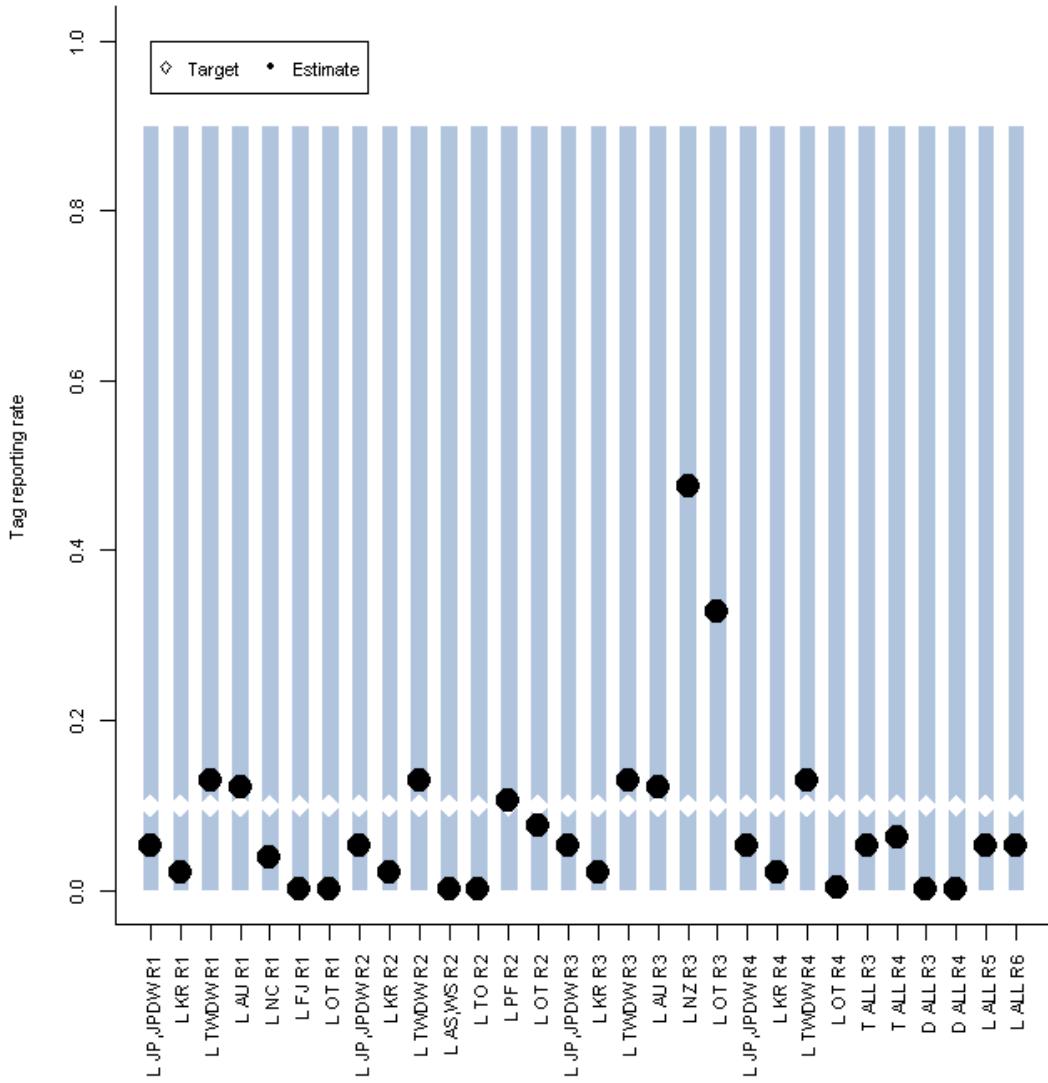
Figure 25: Estimated tag-reporting rates by fishery (black circles). The white diamonds indicate the modes of the priors for each reporting rate and the grey bars indicate a range of ±1 SD.
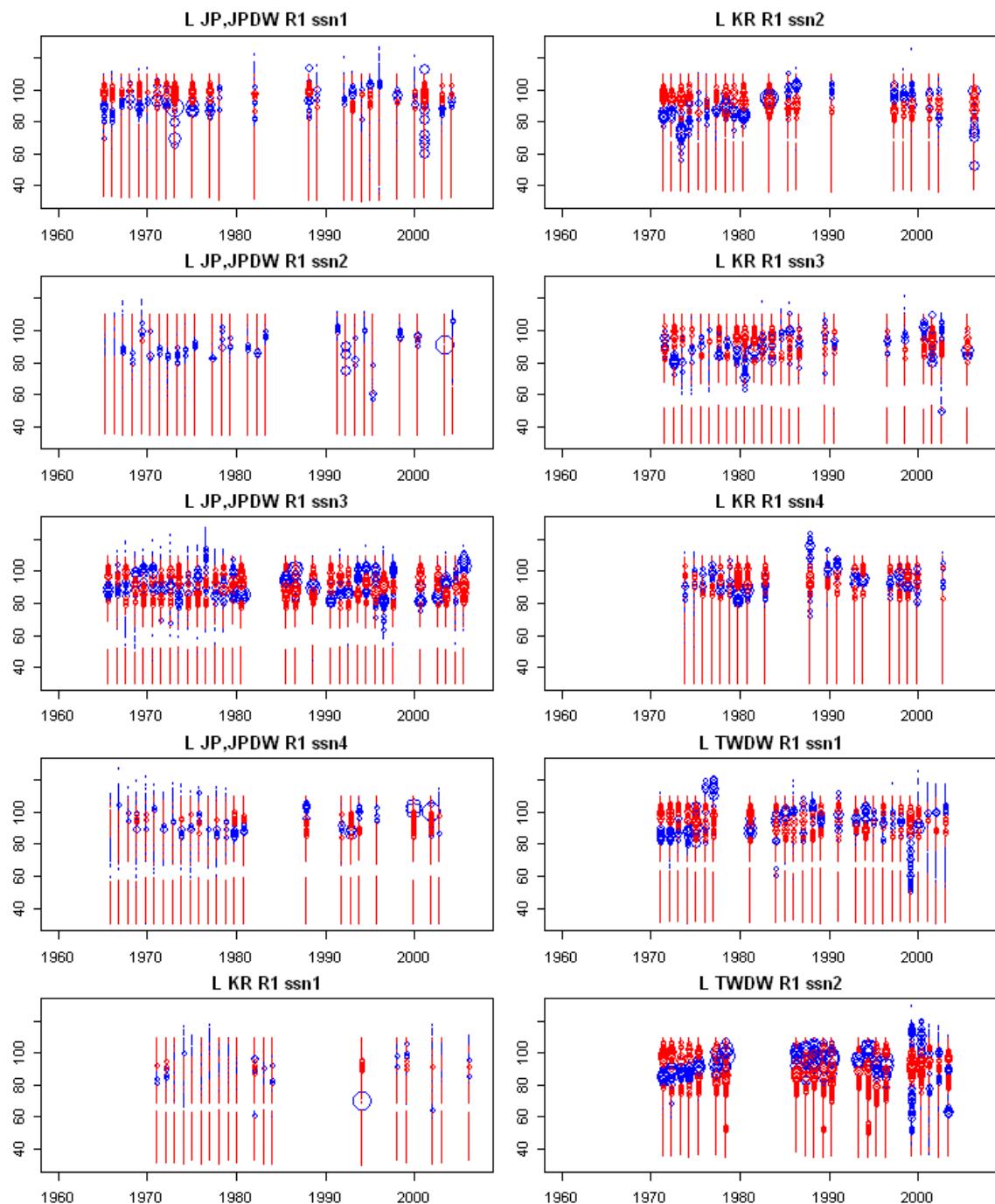
Figure 26a: Length frequency residuals by fishery, year-quarter, and centimetre. Positive (observed > expected) and negative residuals are in blue and red, with the area of the circle proportional to the size of the residual.
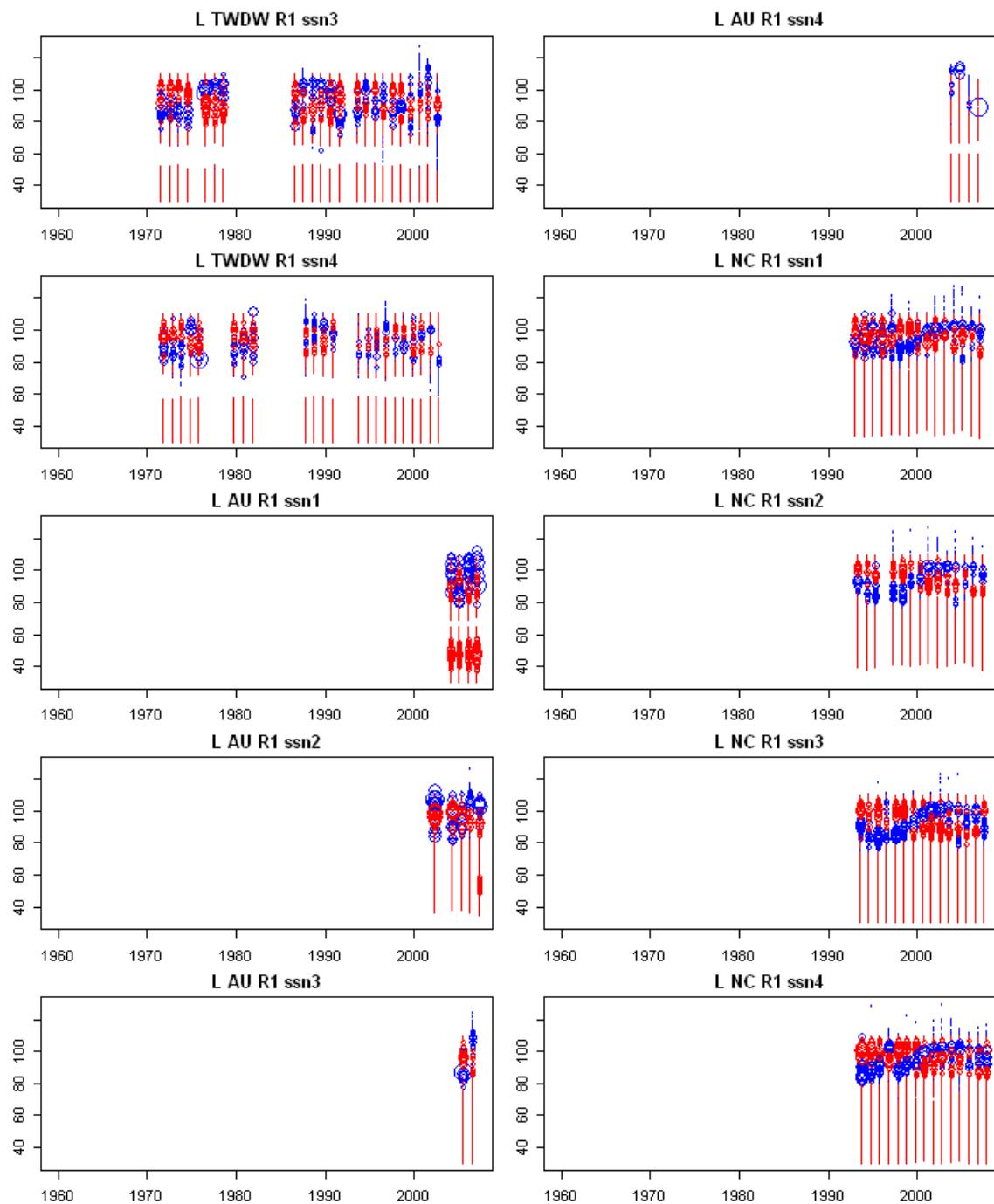
Figure 26b: Length frequency residuals by fishery, year-quarter, and centimetre. Positive (observed > expected) and negative residuals are in blue and red, with the area of the circle proportional to the size of the residual.
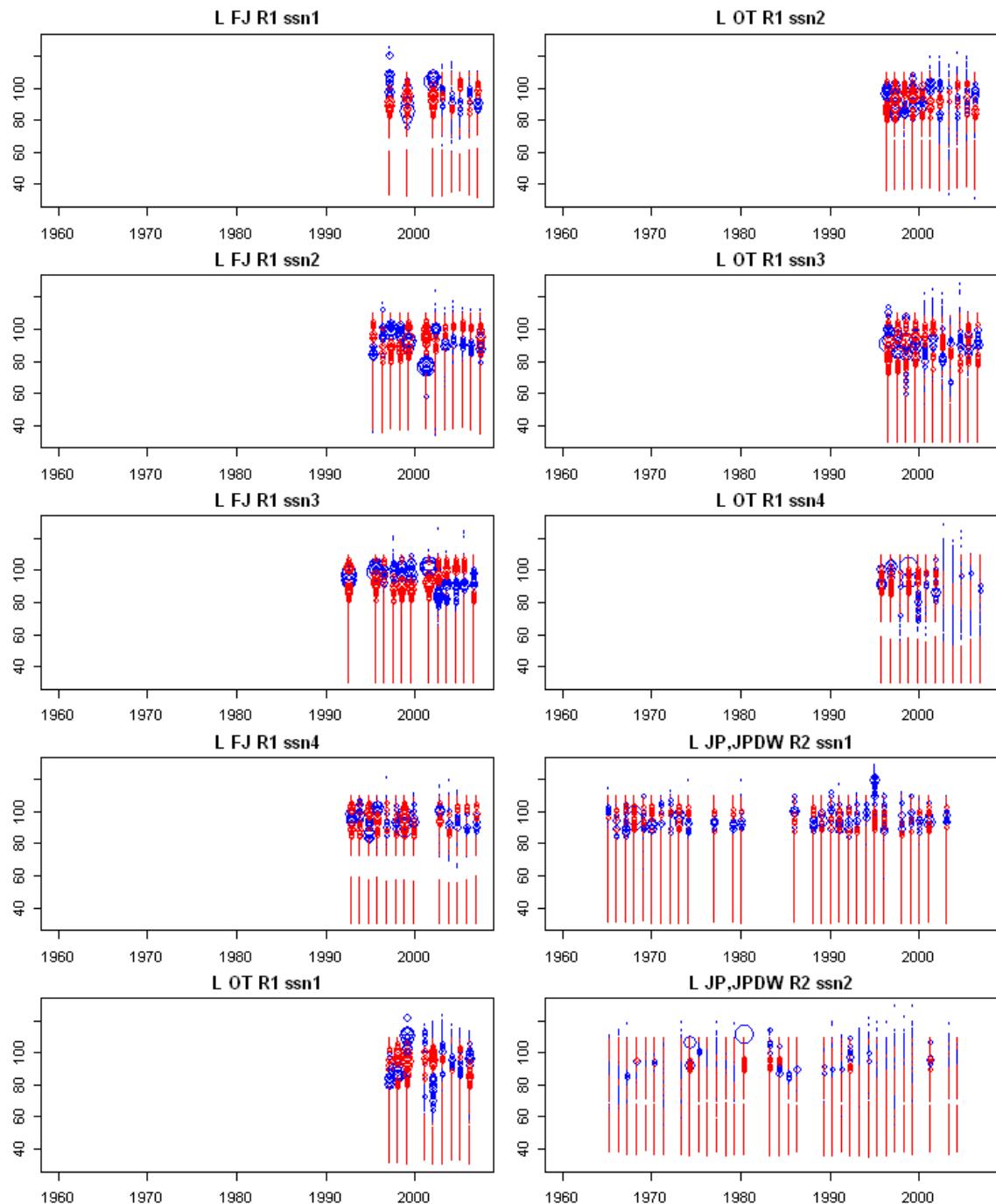
Figure 26c: Length frequency residuals by fishery, year-quarter, and centimetre. Positive (observed > expected) and negative residuals are in blue and red, with the area of the circle proportional to the size of the residual.
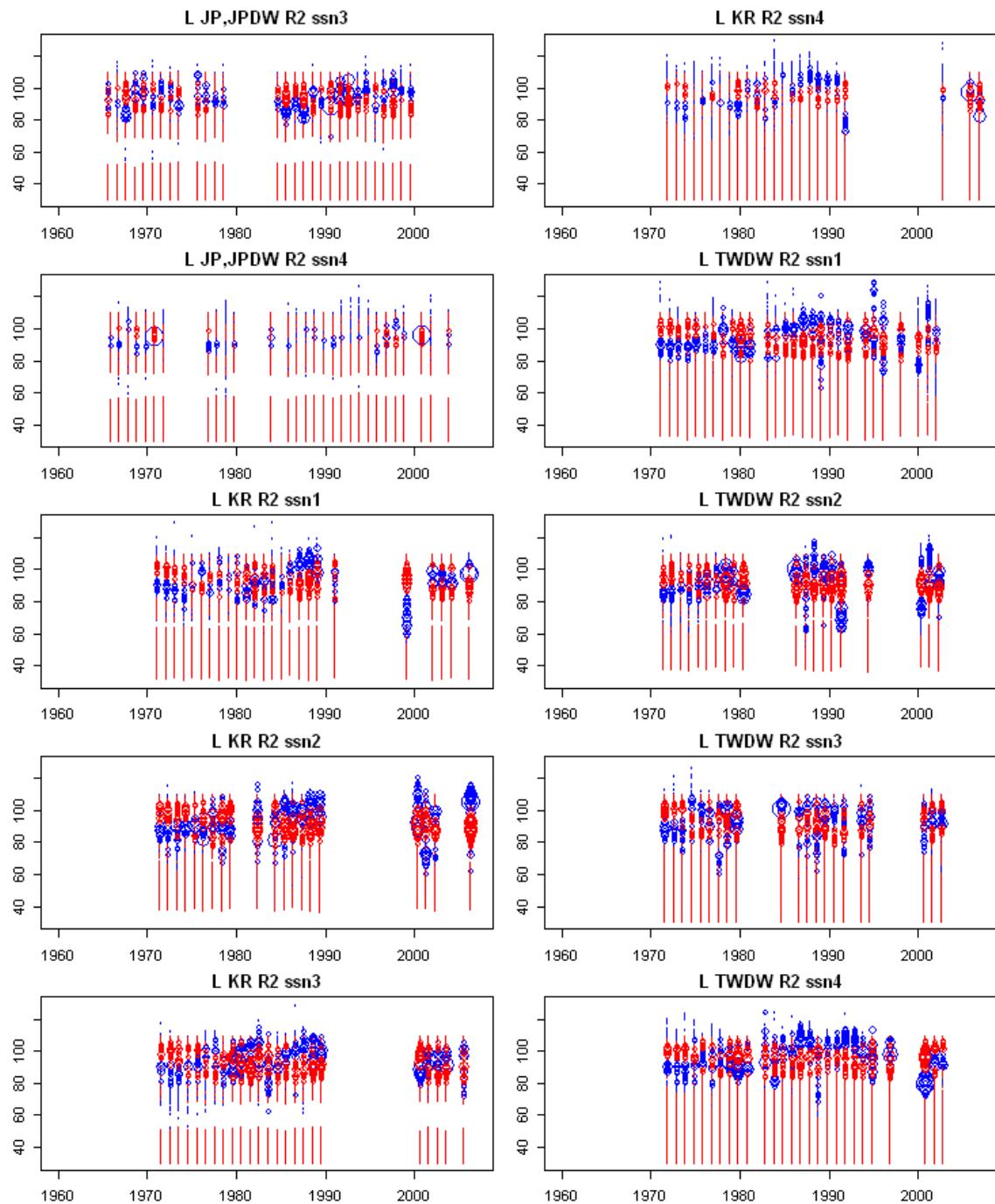
Figure 26d: Length frequency residuals by fishery, year-quarter, and centimetre. Positive (observed > expected) and negative residuals are in blue and red, with the area of the circle proportional to the size of the residual.
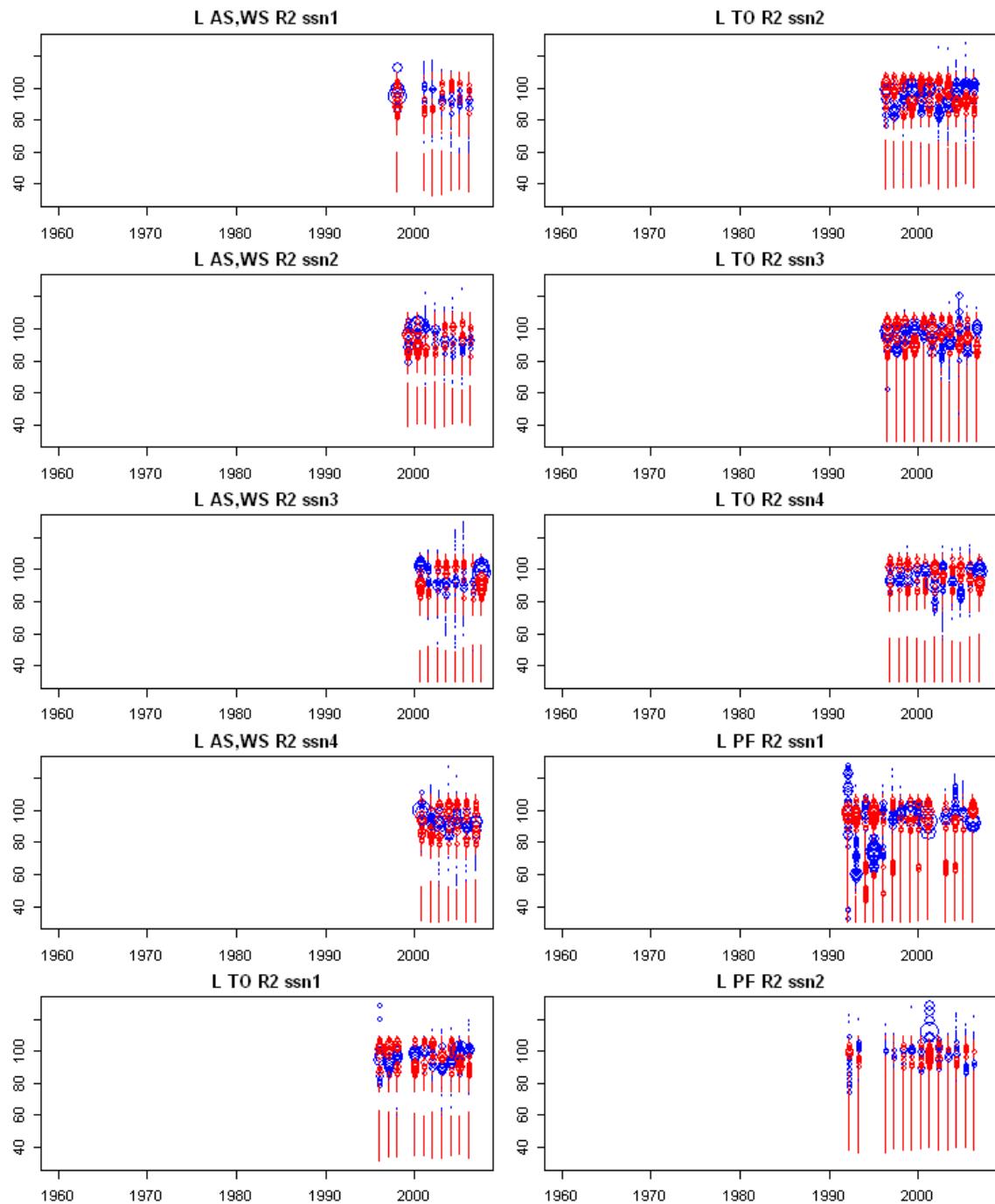
Figure 26e: Length frequency residuals by fishery, year-quarter, and centimetre. Positive (observed > expected) and negative residuals are in blue and red, with the area of the circle proportional to the size of the residual.
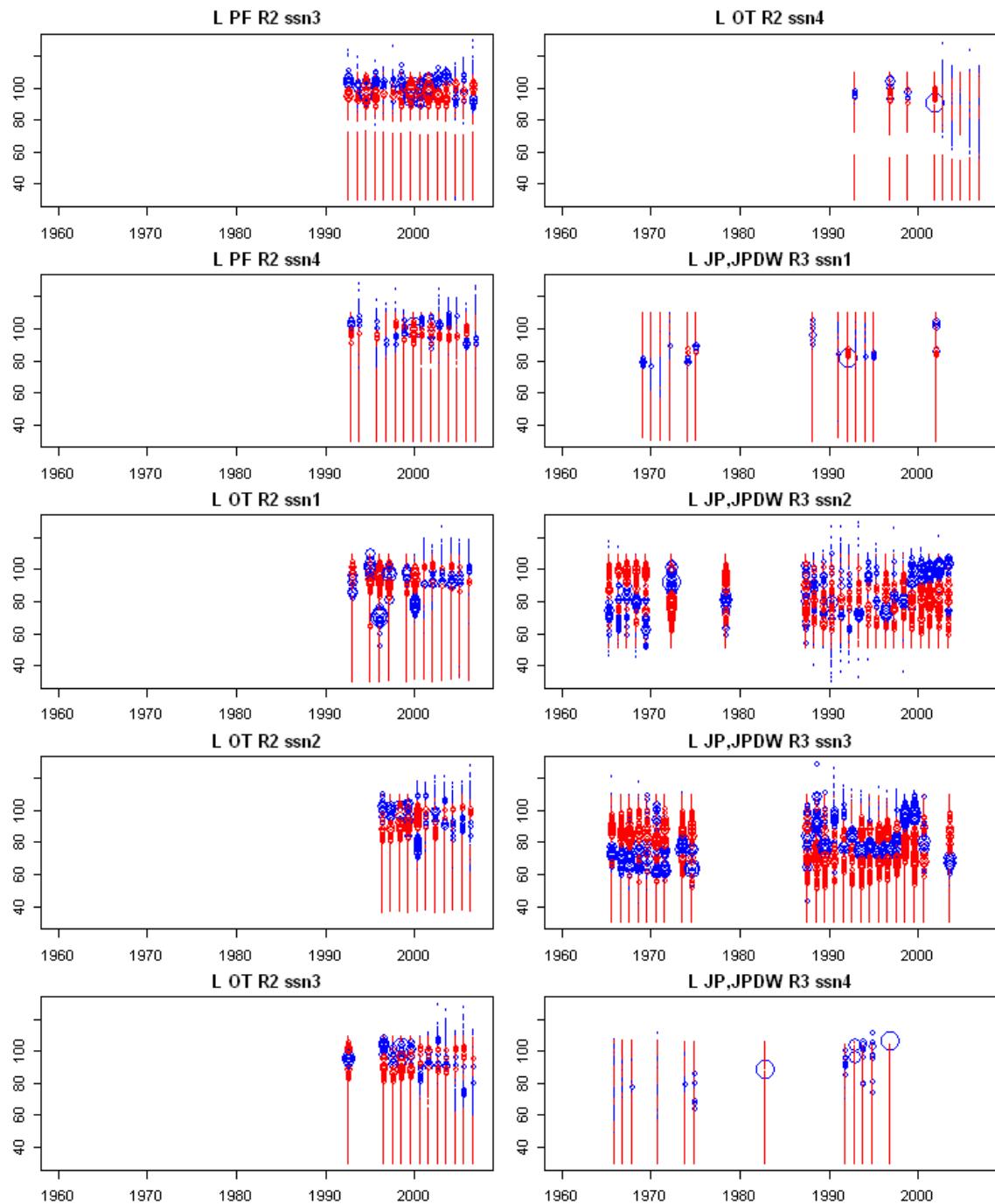
Figure 26f: Length frequency residuals by fishery, year-quarter, and centimetre. Positive (observed > expected) and negative residuals are in blue and red, with the area of the circle proportional to the size of the residual.
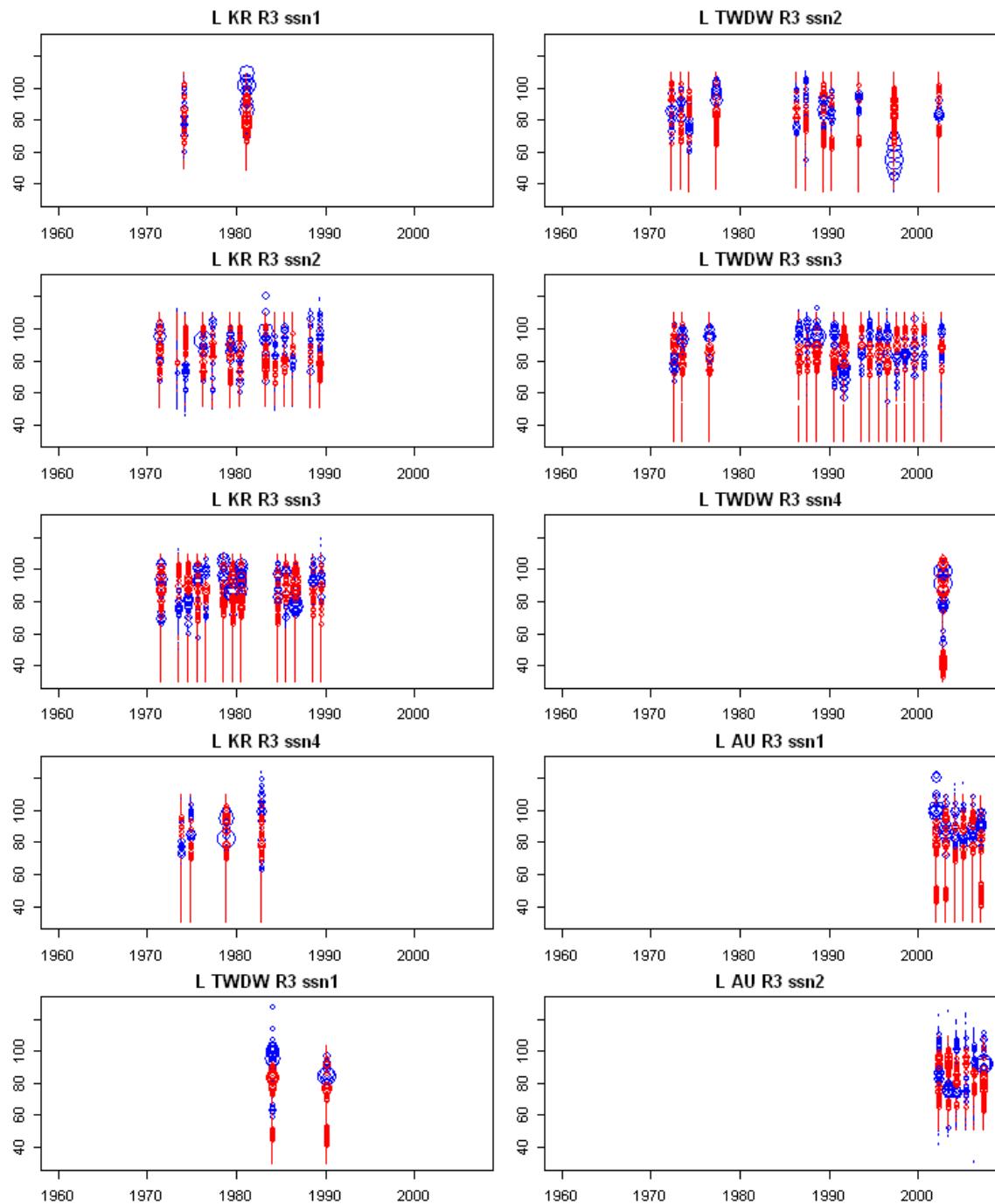
Figure 26g: Length frequency residuals by fishery, year-quarter, and centimetre. Positive (observed > expected) and negative residuals are in blue and red, with the area of the circle proportional to the size of the residual.
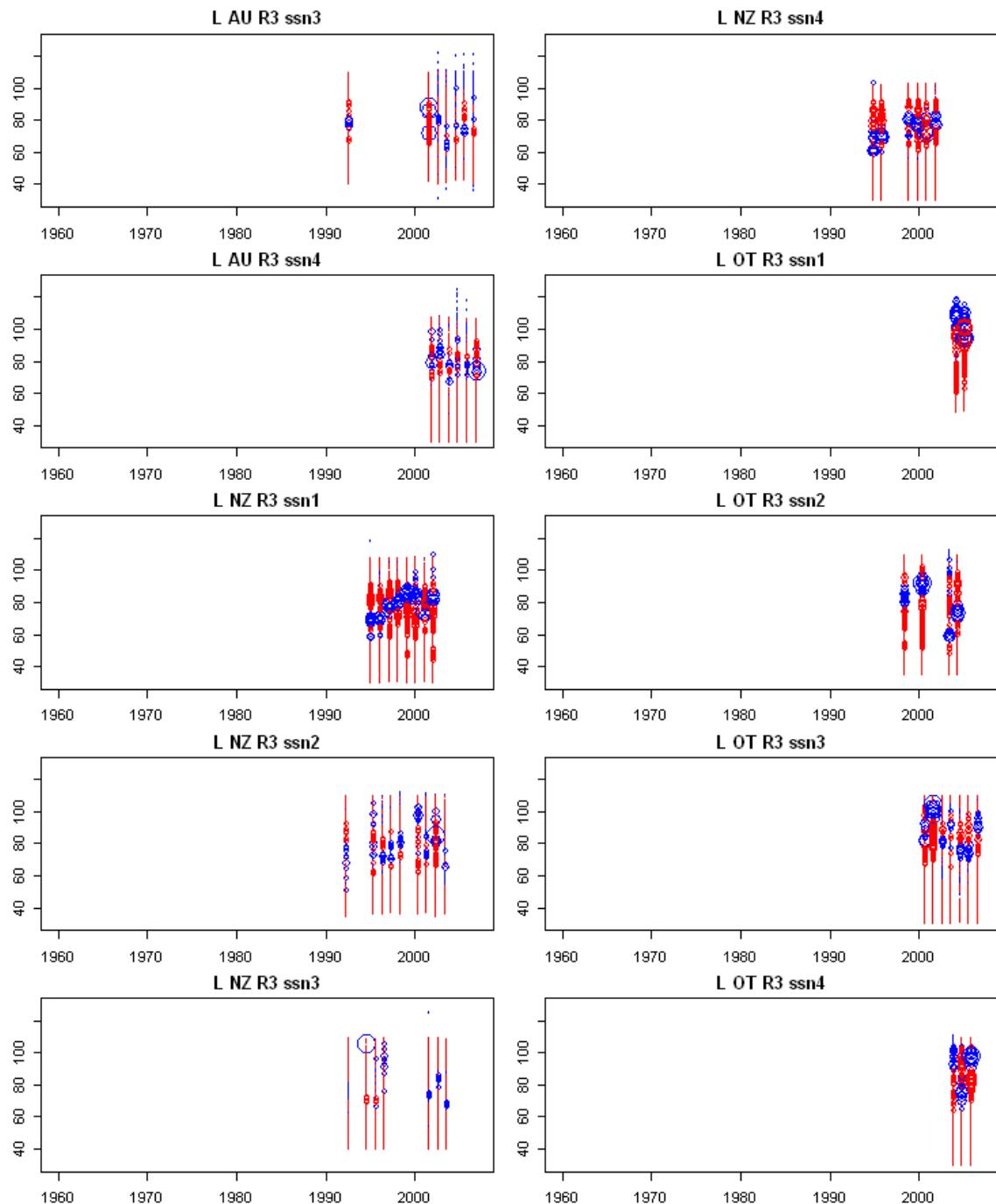
Figure 26h: Length frequency residuals by fishery, year-quarter, and centimetre. Positive (observed > expected) and negative residuals are in blue and red, with the area of the circle proportional to the size of the residual.
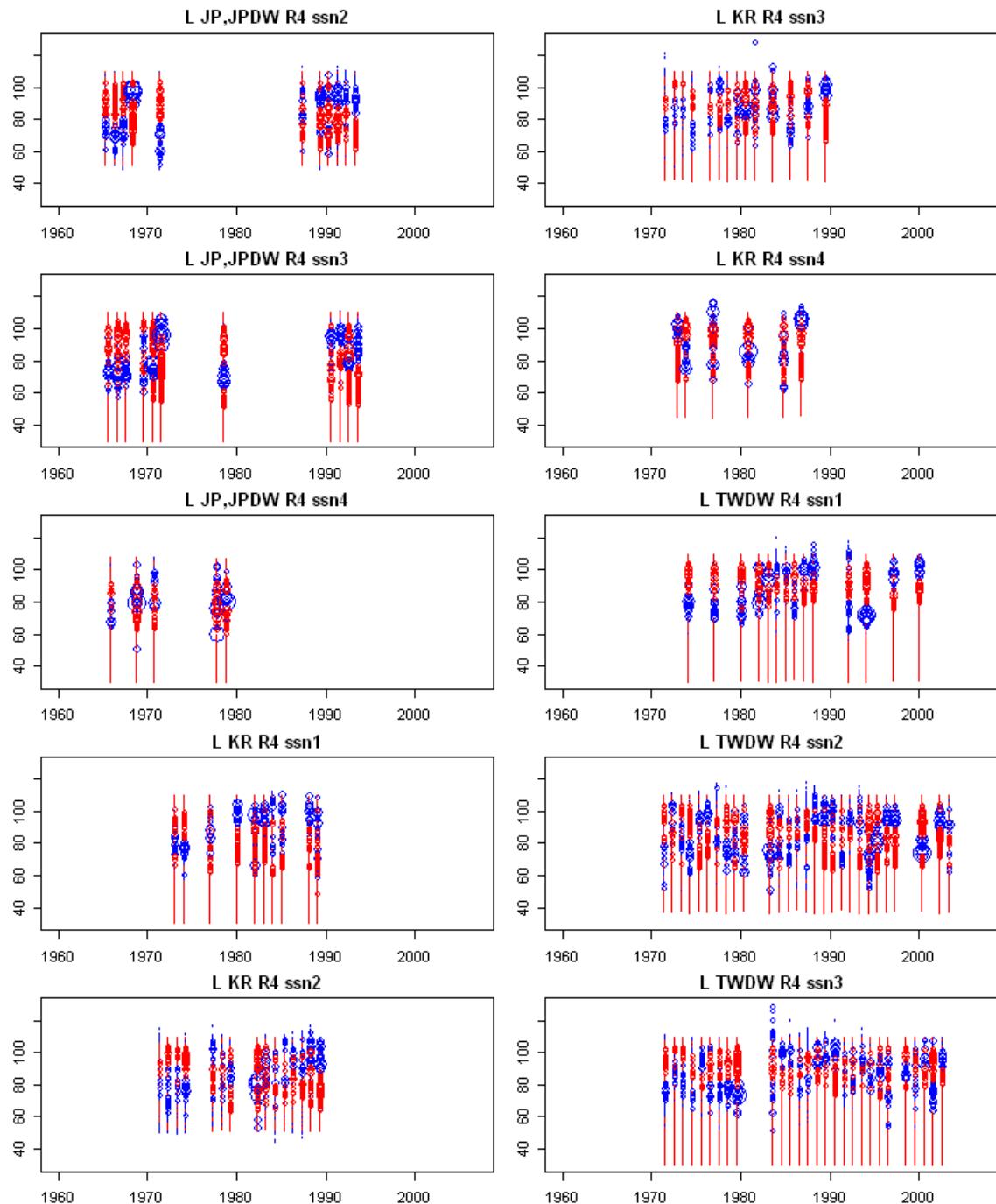
Figure 26i: Length frequency residuals by fishery, year-quarter, and centimetre. Positive (observed > expected) and negative residuals are in blue and red, with the area of the circle proportional to the size of the residual.
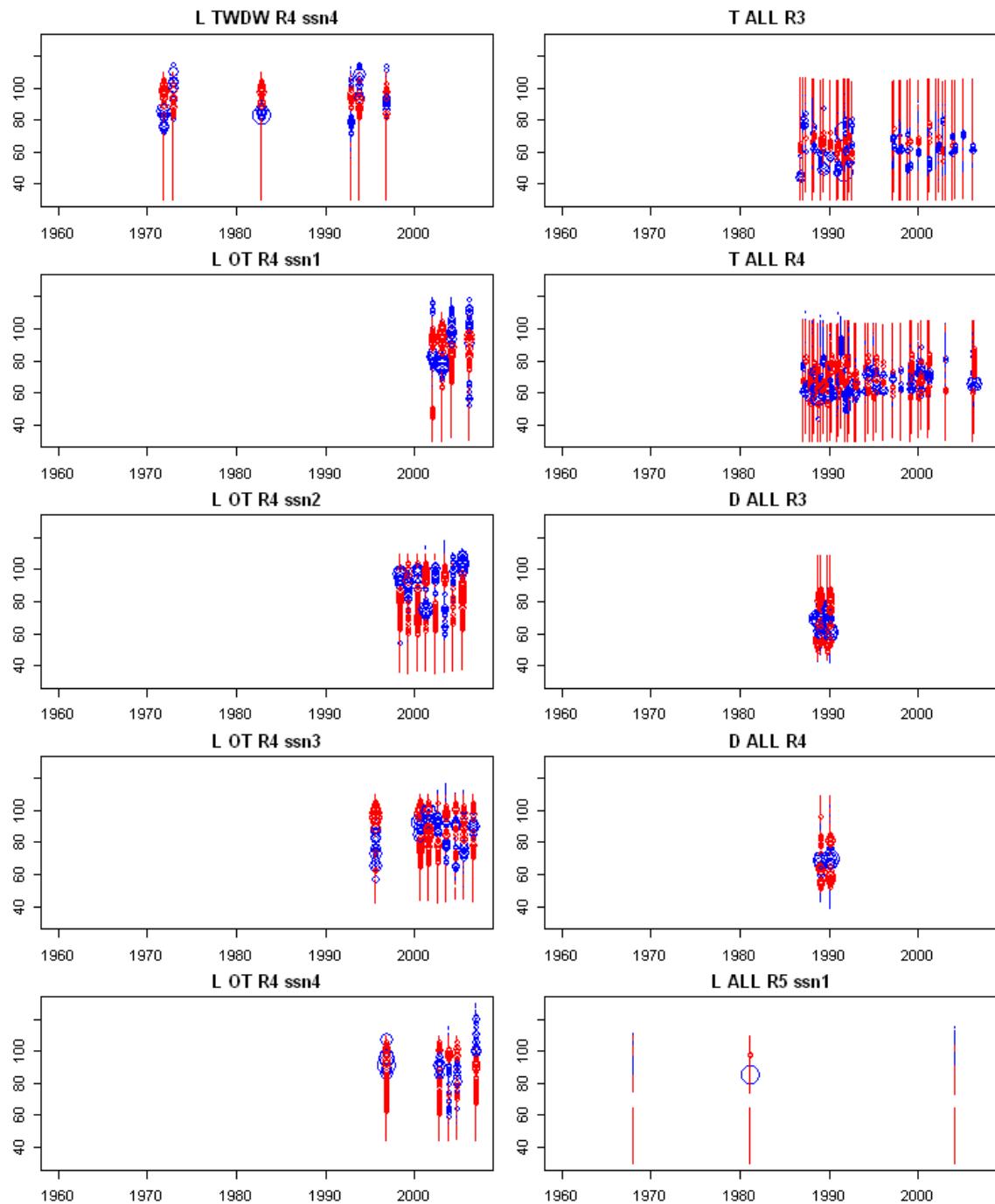
Figure 26j: Length frequency residuals by fishery, year-quarter, and centimetre. Positive (observed > expected) and negative residuals are in blue and red, with the area of the circle proportional to the size of the residual.
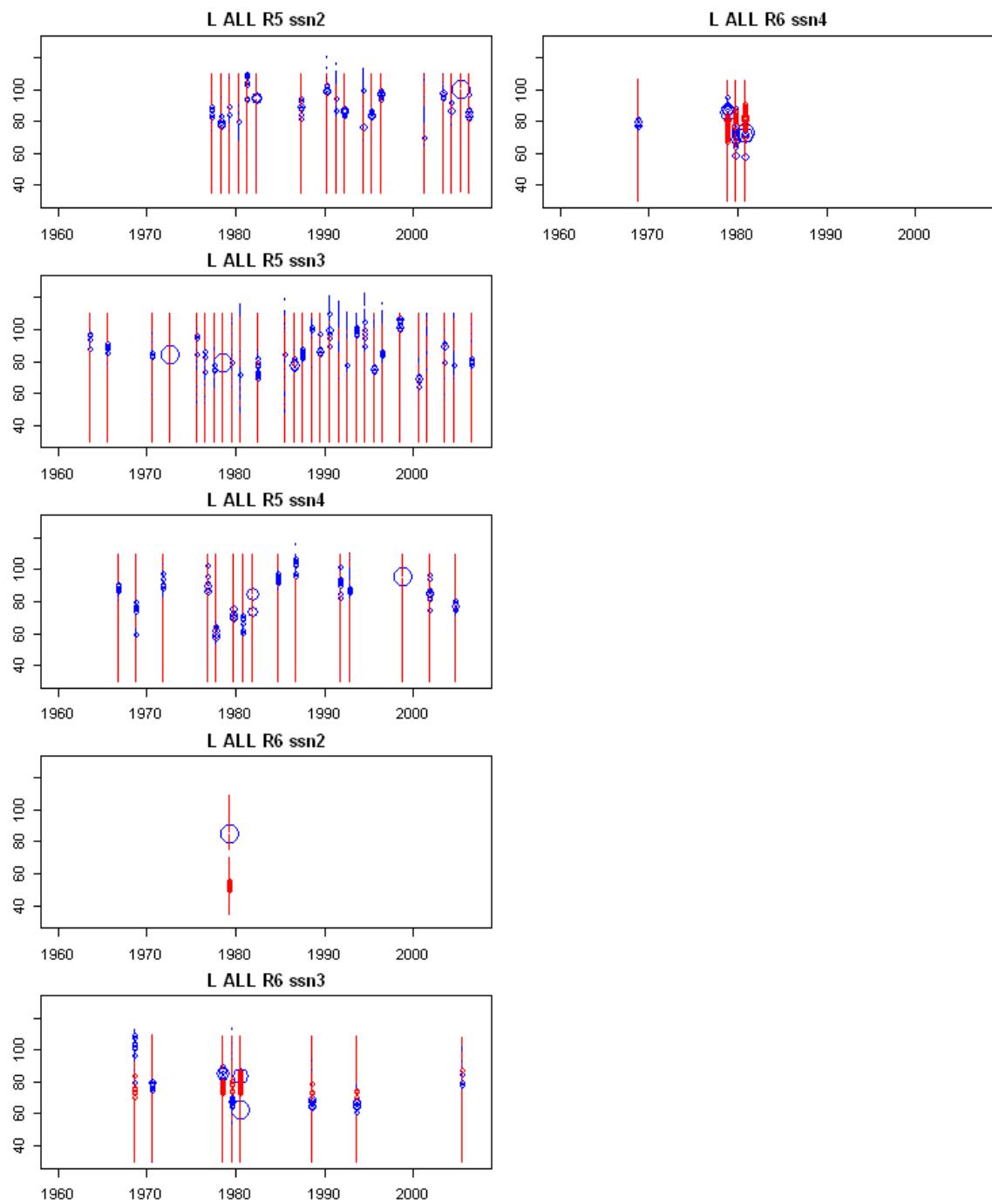
Figure 26k: Length frequency residuals by fishery, year-quarter, and centimetre. Positive (observed > expected) and negative residuals are in blue and red, with the area of the circle proportional to the size of the residual.
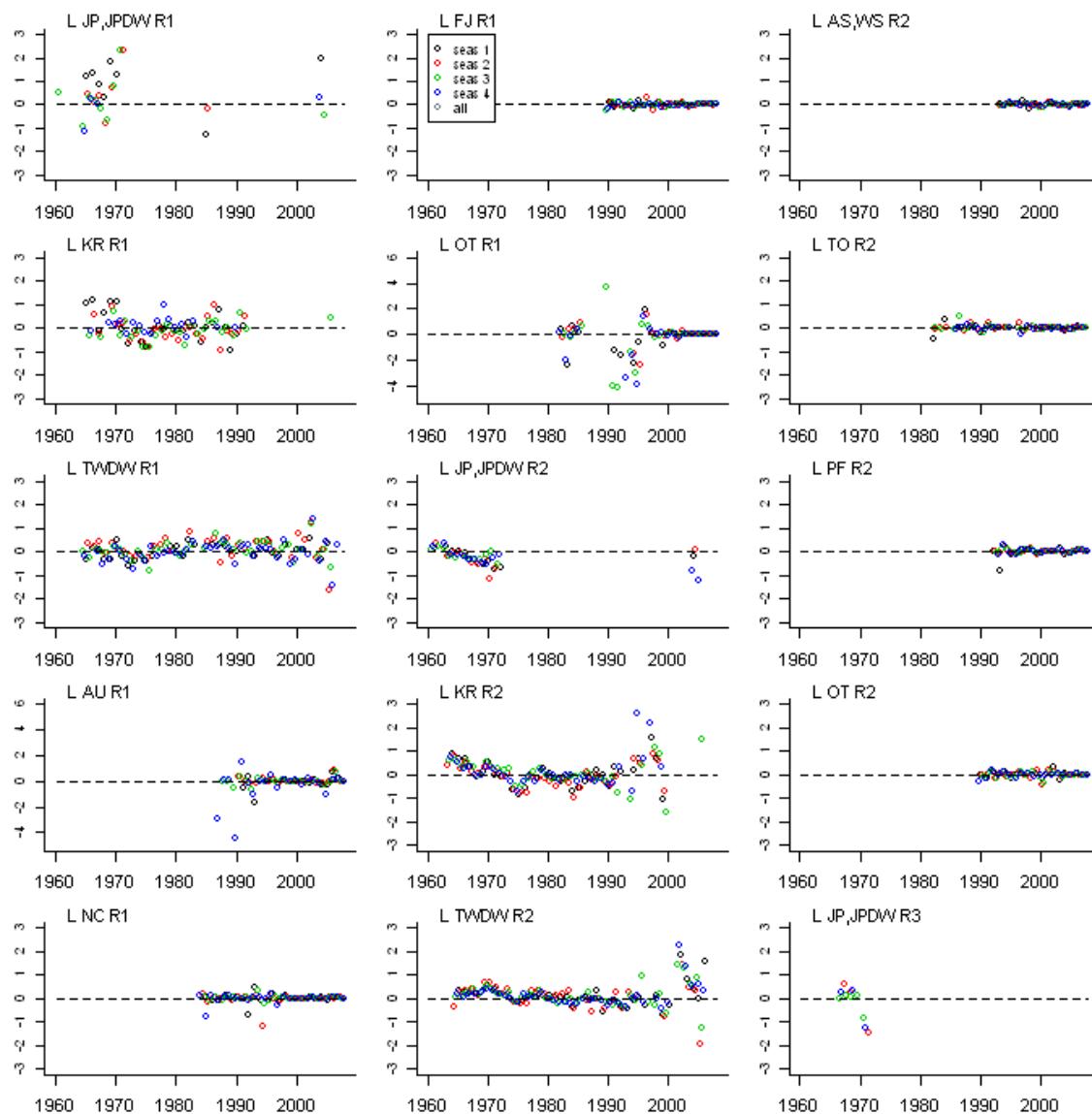
Figure 27a: Quarterly effort deviates by fishery.
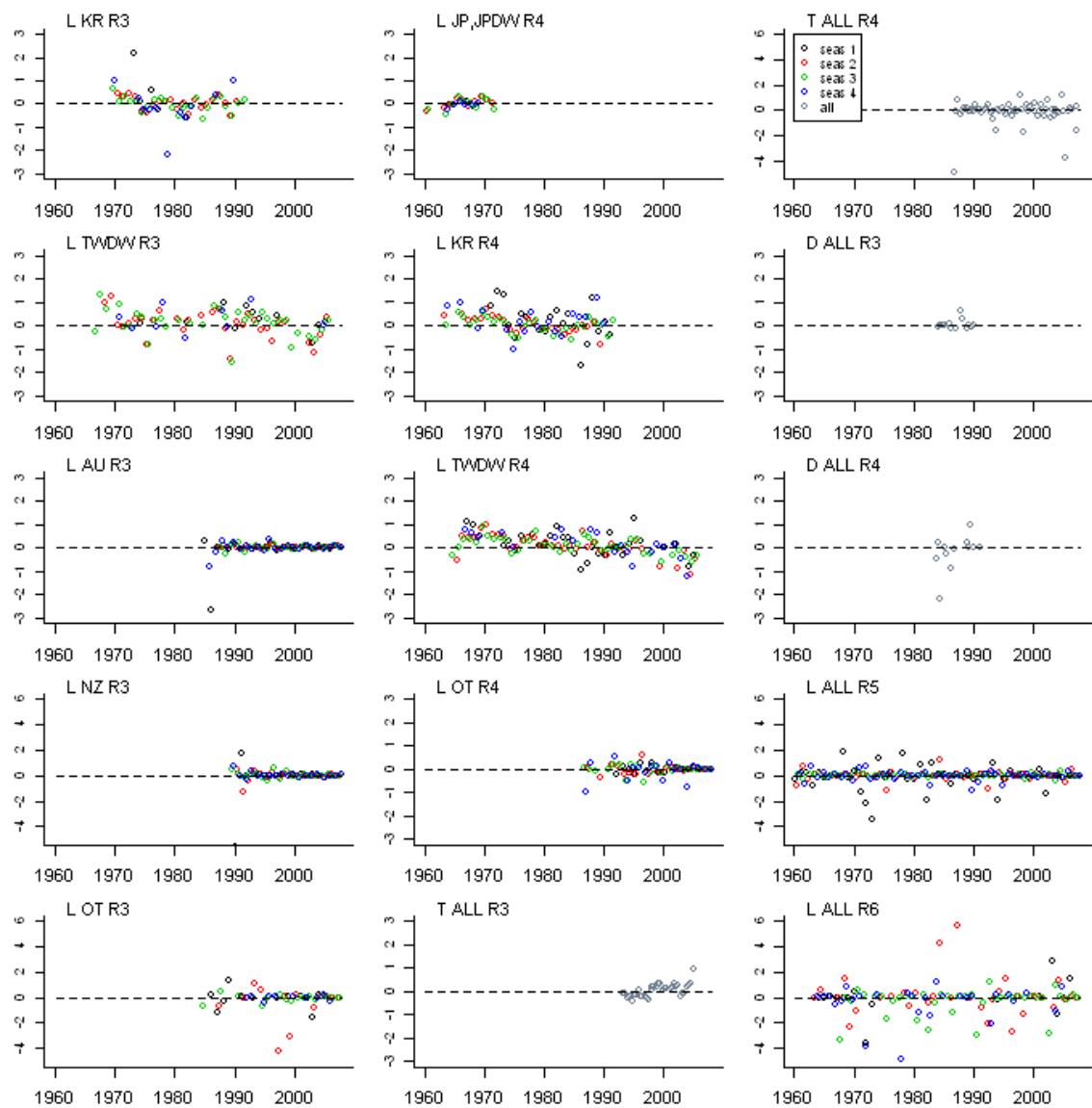
Figure 27b: Quarterly effort deviates by fishery.
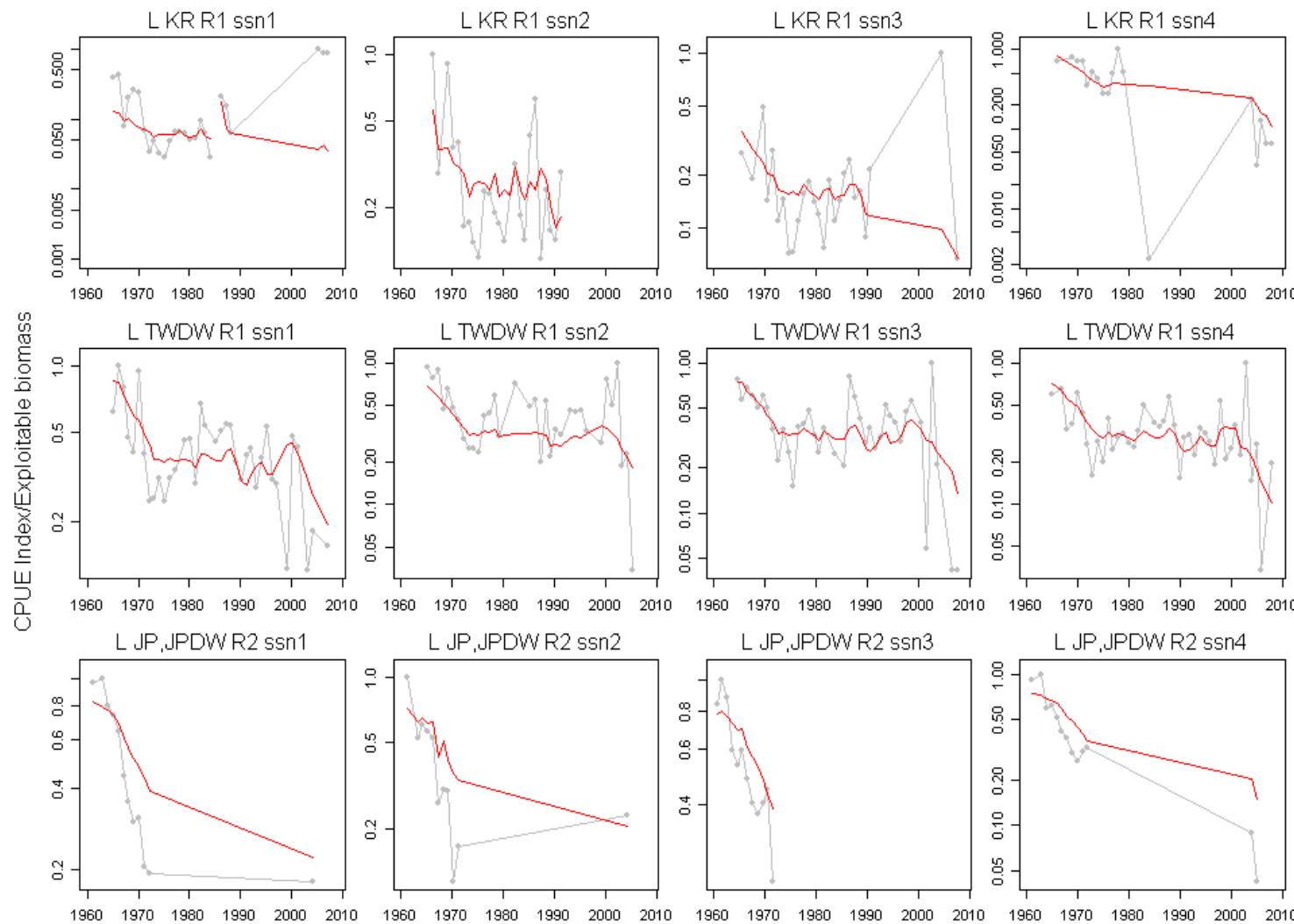
Figure 28: A comparison of the observed catch rate (number of fish) (grey points and line) and the predicted exploitable biomass from the quarterly observations of catch and effort from each of the standardized fisheries (red line).
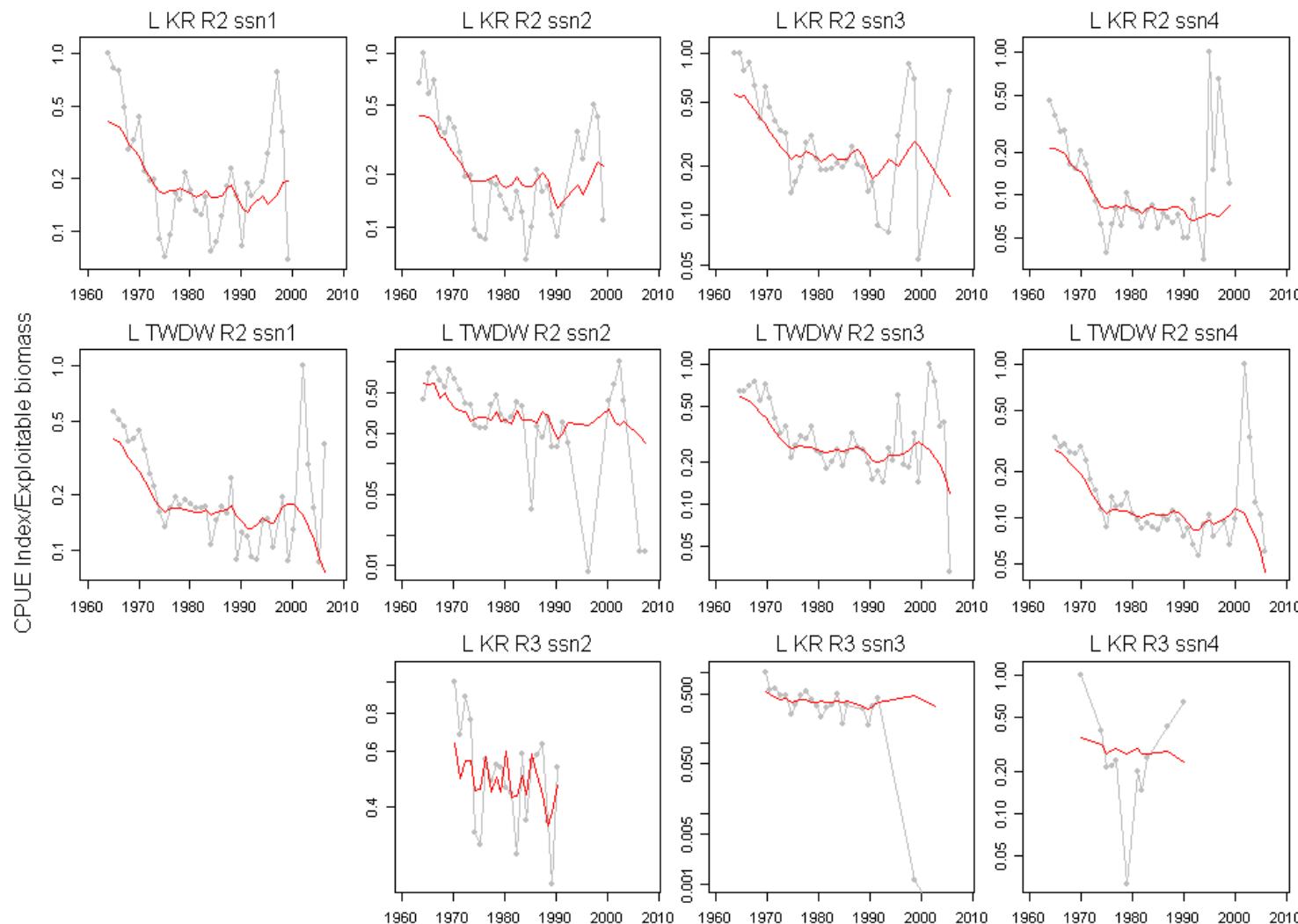
Figure 28b: A comparison of the observed catch rate (number of fish) (grey points and line) and the predicted exploitable biomass from the quarterly observations of catch and effort from each of the standardized fisheries (red line).
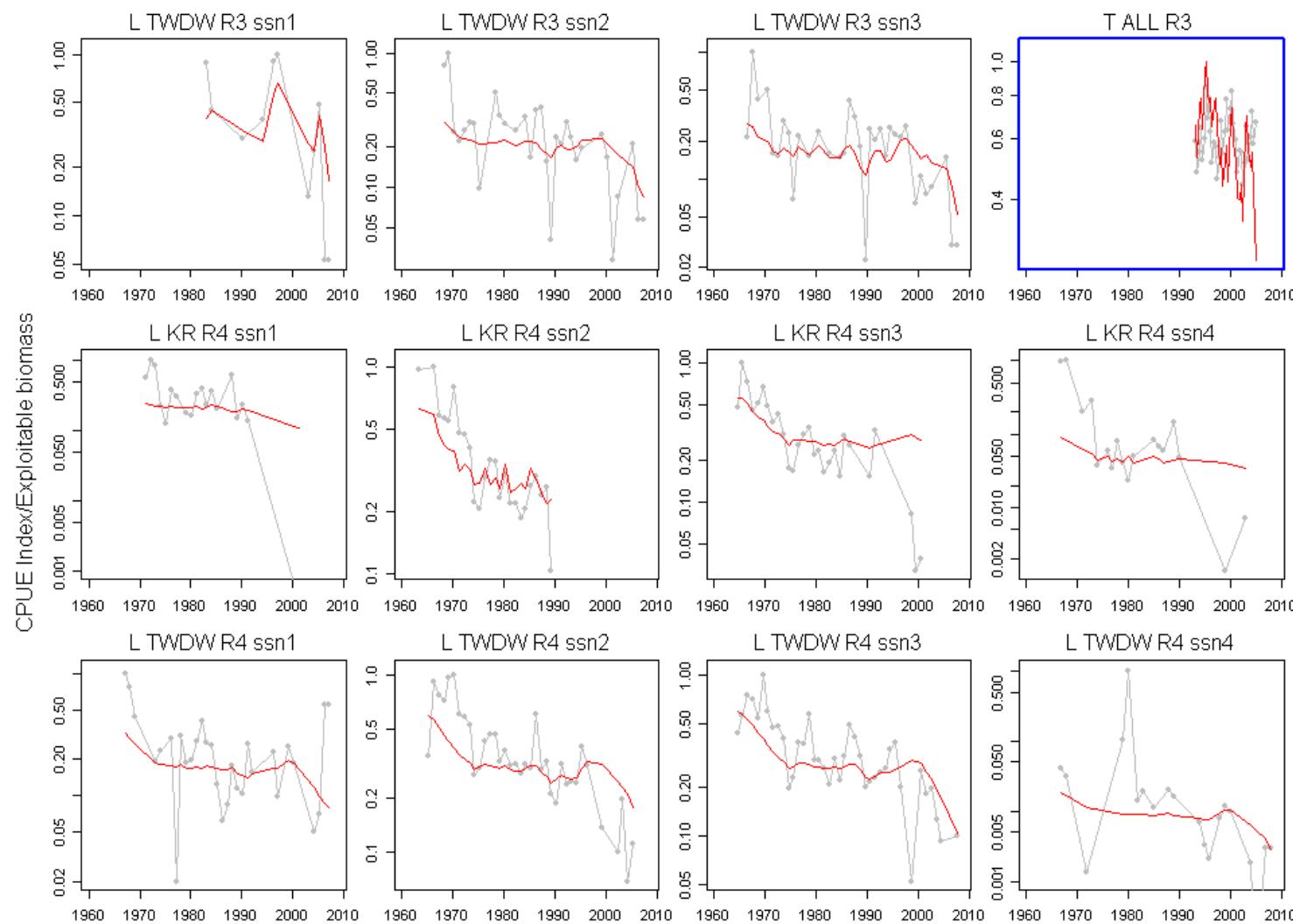
Figure 28c: A comparison of the observed catch rate (number of fish) (grey points and line) and the predicted exploitable biomass from the quarterly observations of catch and effort from each of the standardized fisheries (red line).
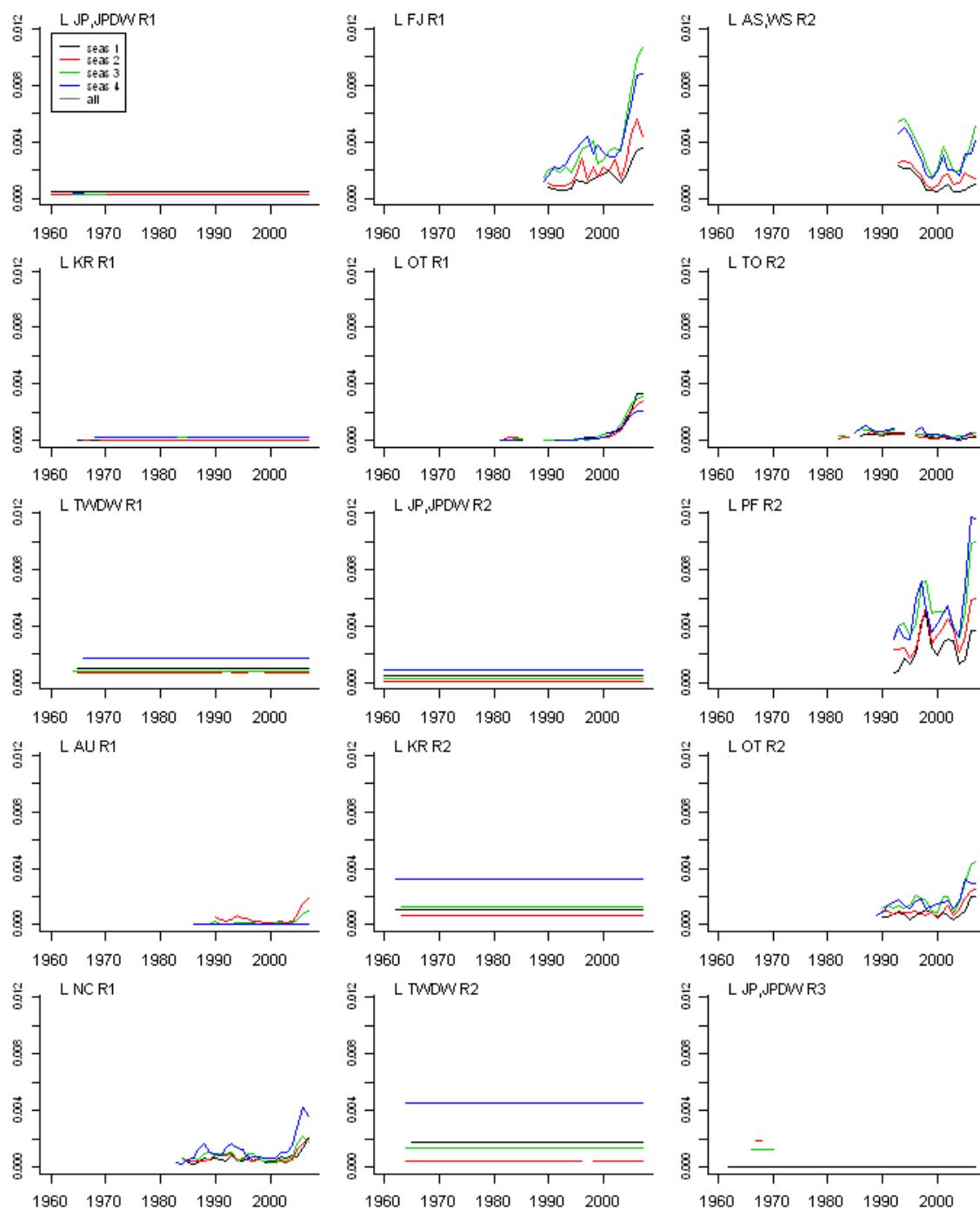
Figure 29a: Annualized trends in catchability by fishery.
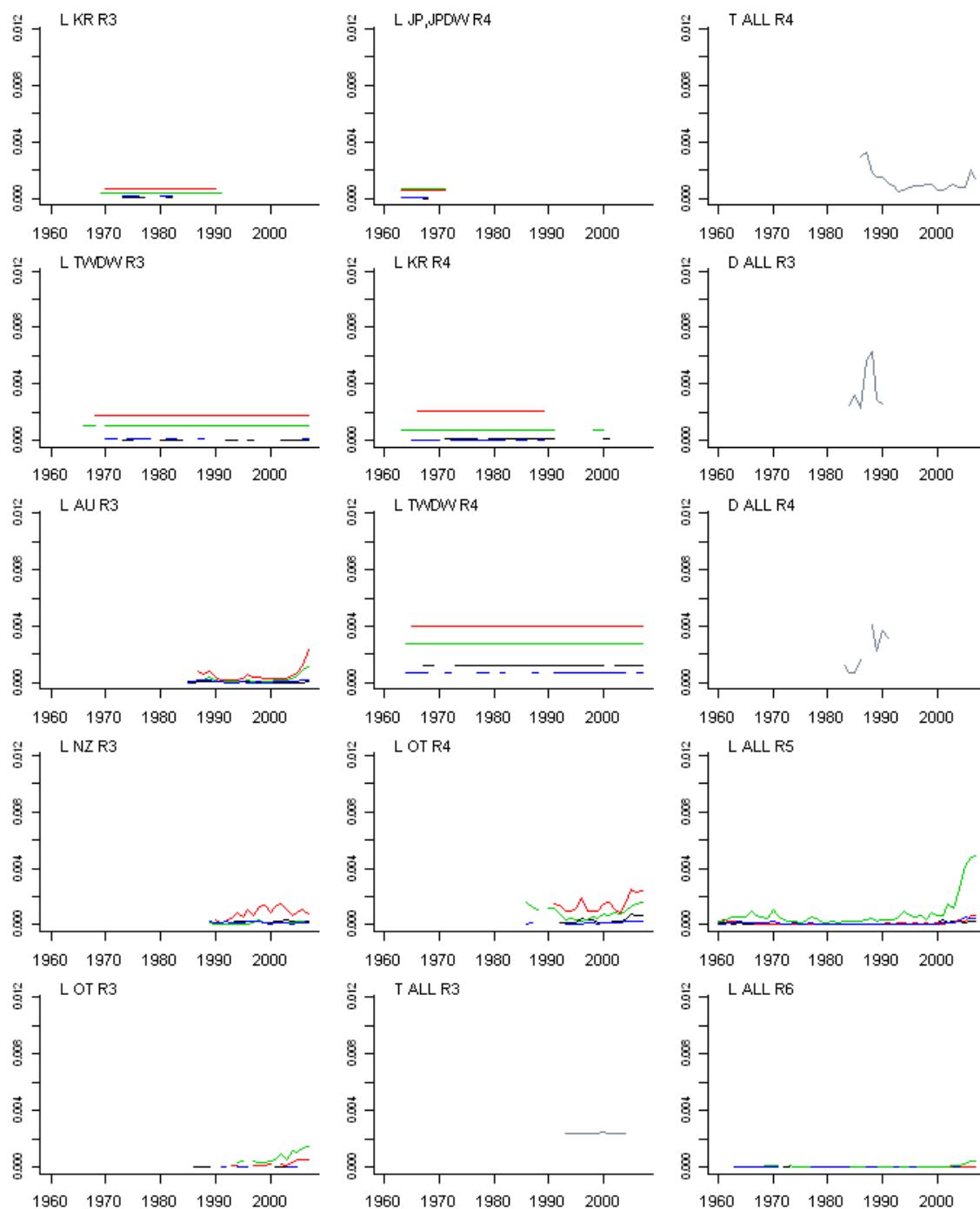
Figure 29b: Annualized trends in catchability by fishery
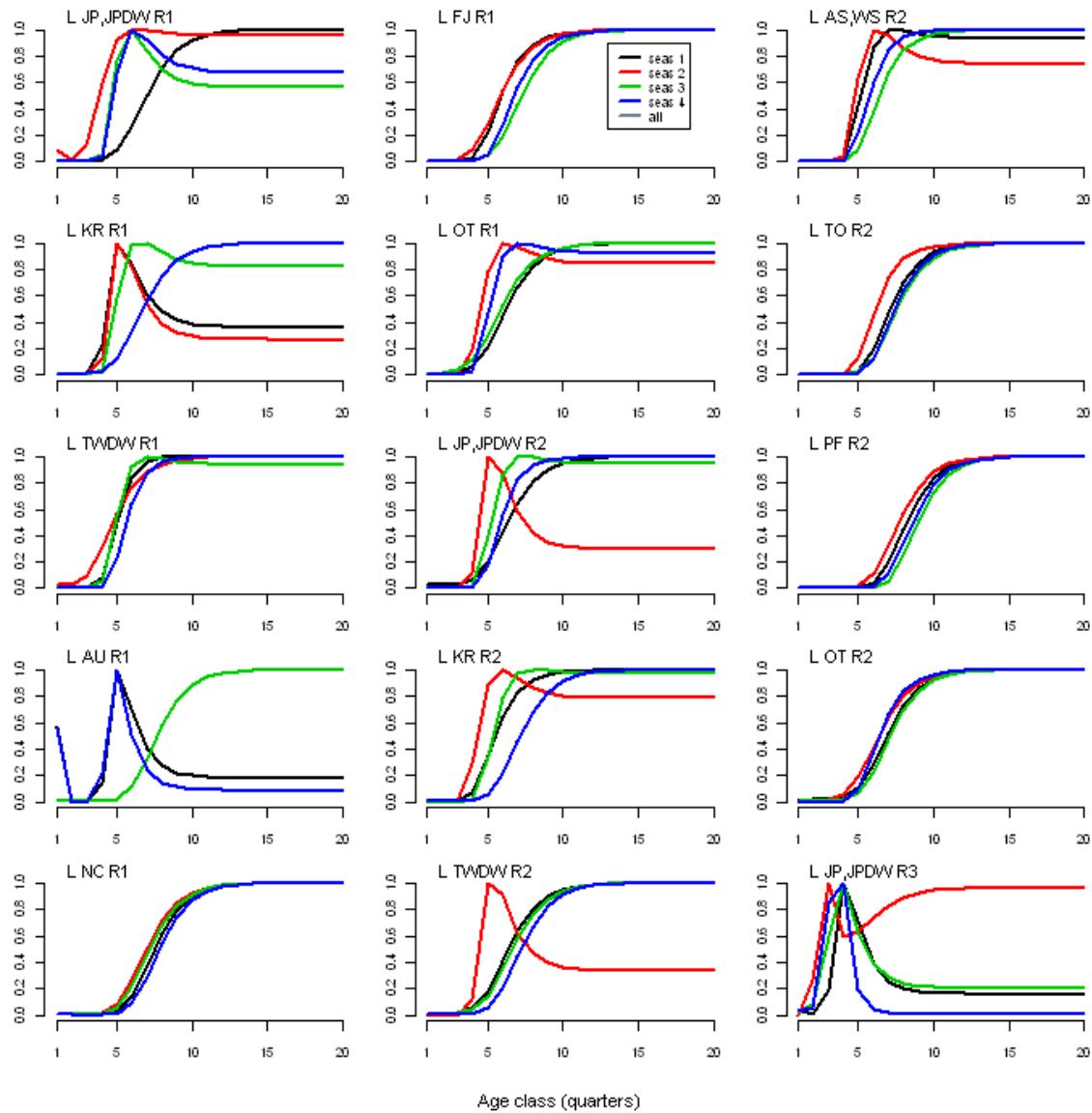
Figure 30a: Selectivity at age (years) by fishery
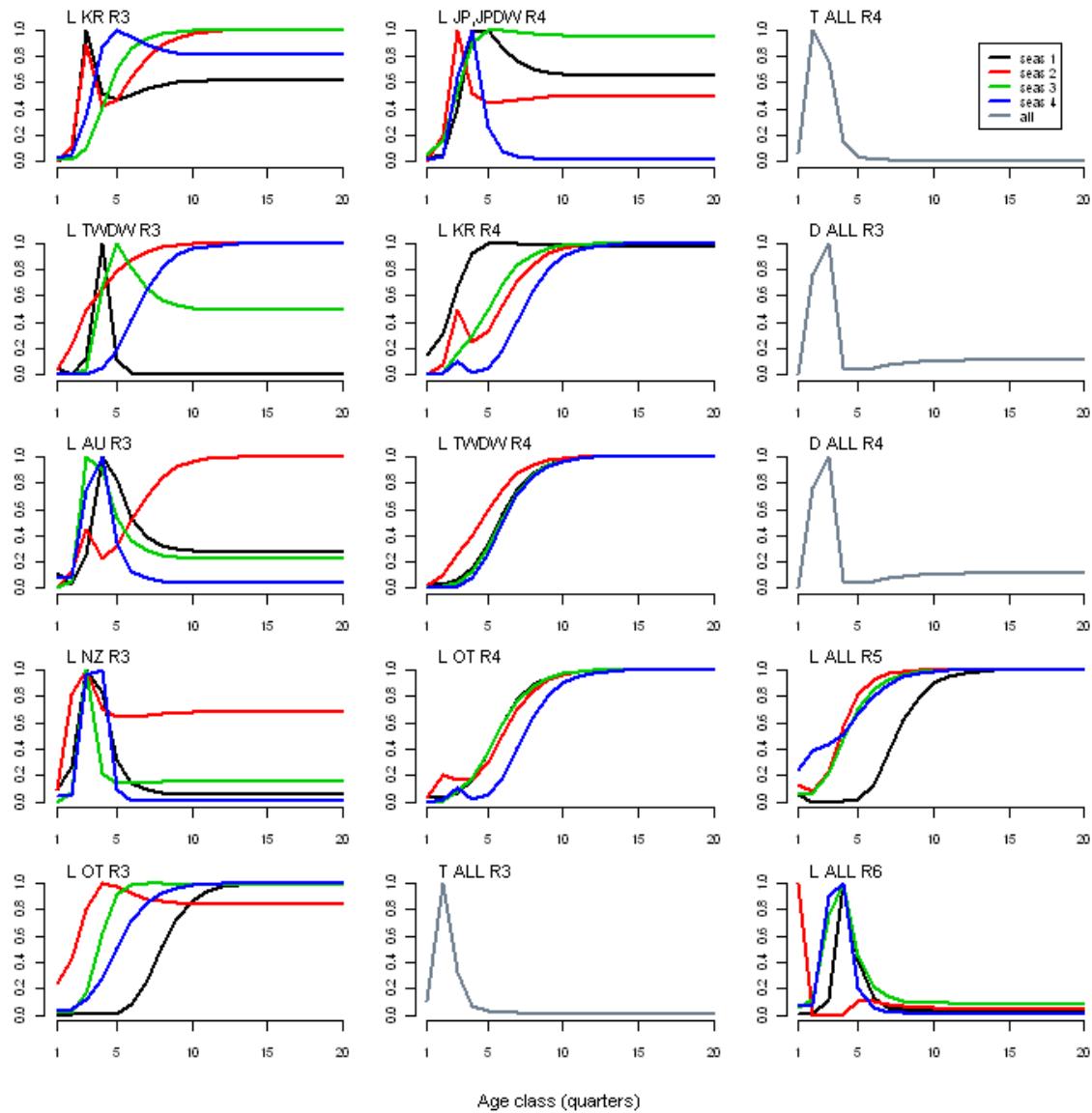
Figure 30b: Selectivity at age (years) by fishery
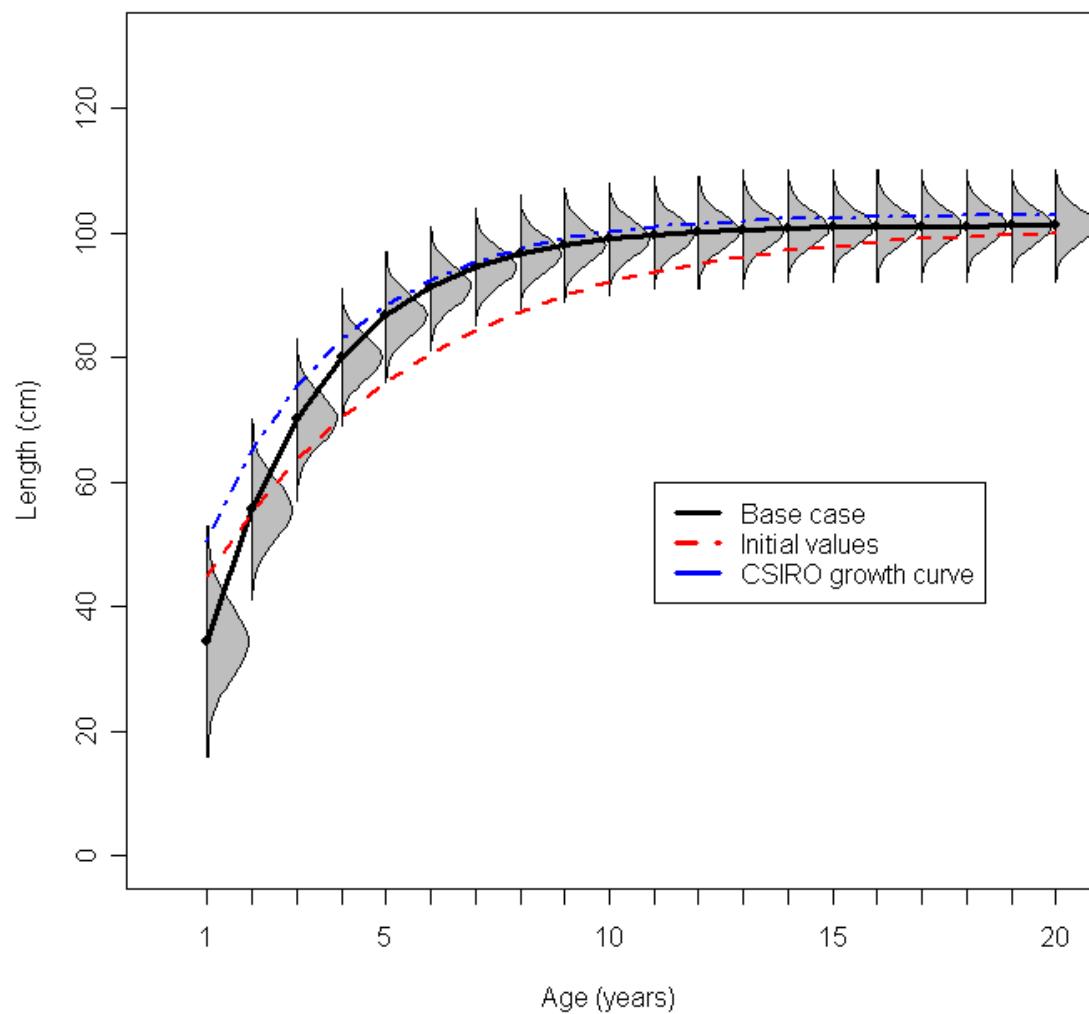
Figure 31: The estimated length (fork length) at age (years) (solid line) and the 95% confidence interval. The dashed line represents the initial values included in the model from the von Bertalanffy parameters.
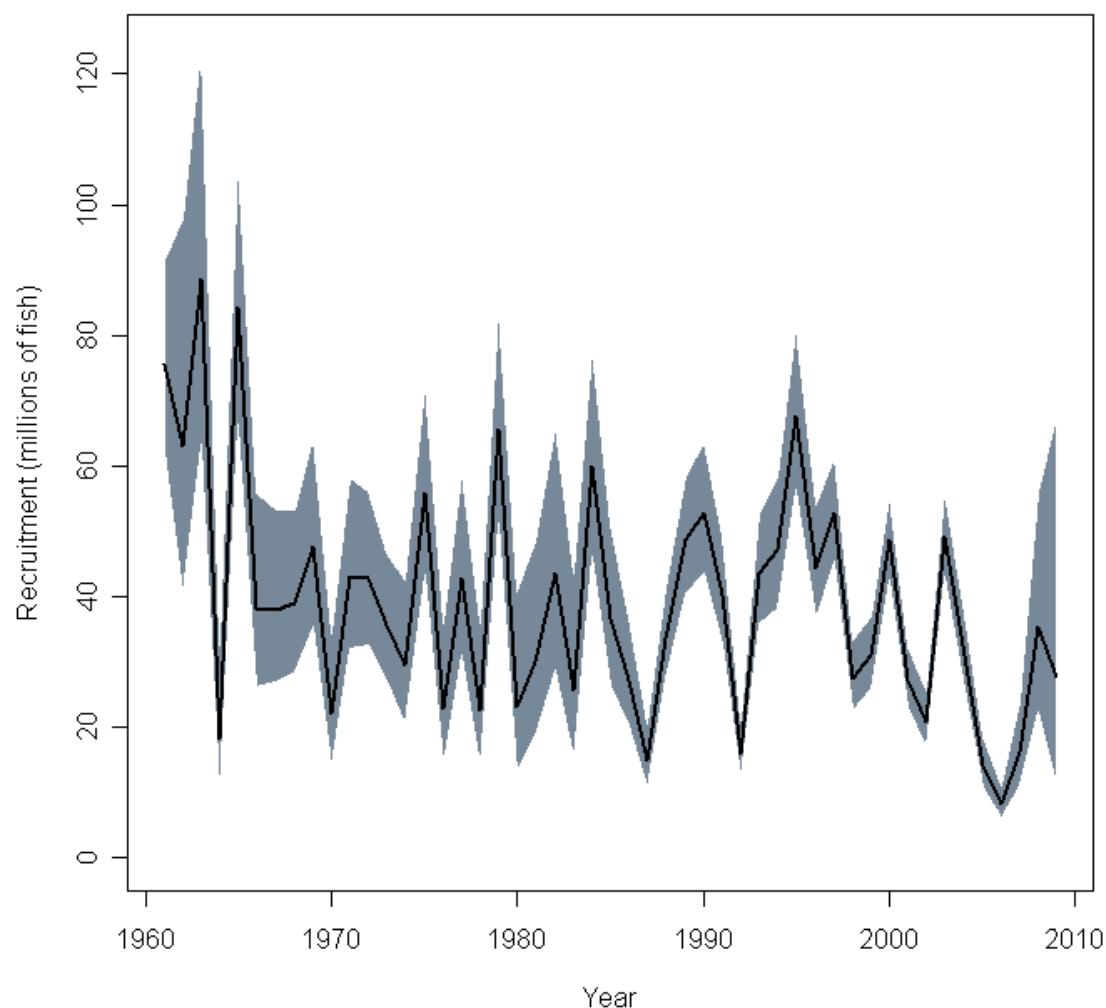
Figure 32: Annual recruitment (number of fish) estimates from the one region model. The shaded area indicates the approximate 95% confidence intervals.
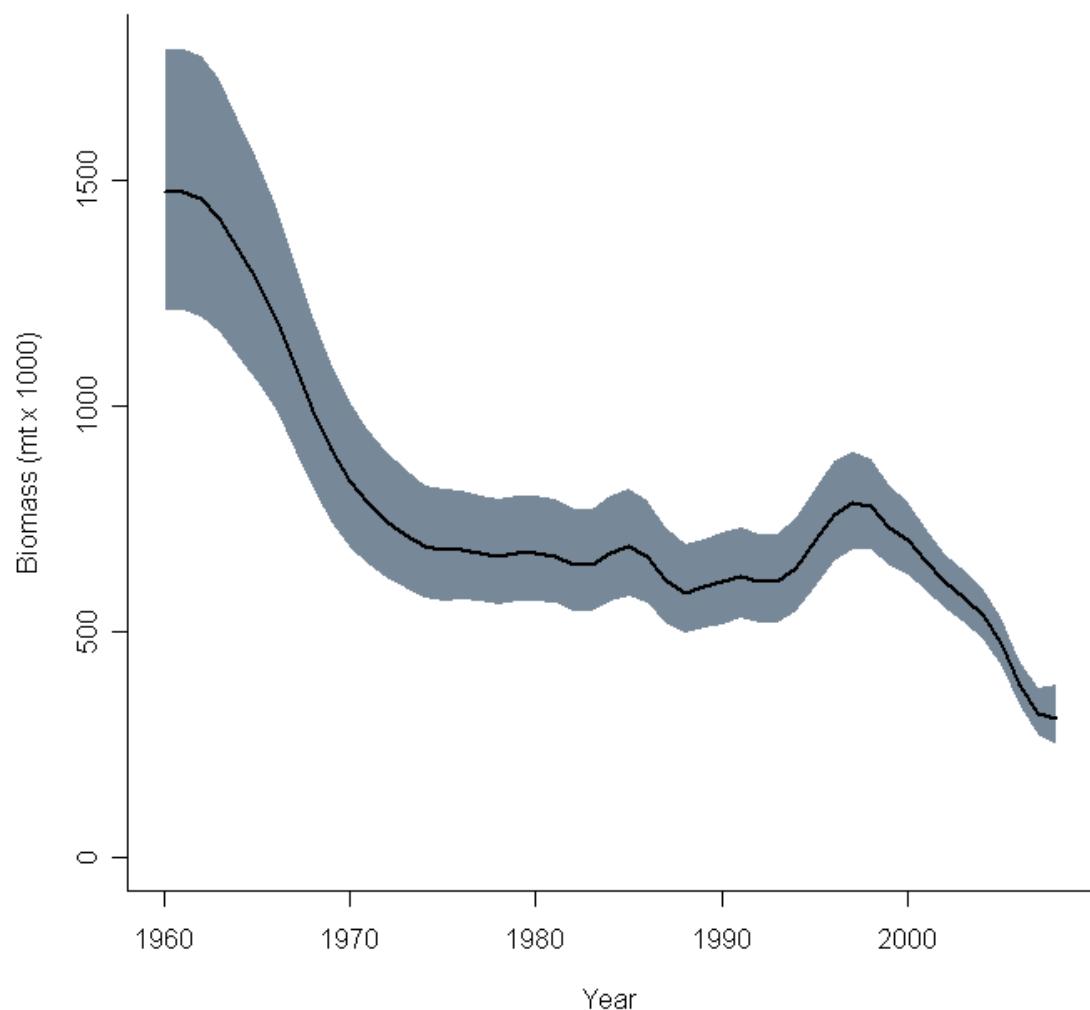
Figure 33: Annual estimates of total biomass (thousands of metric tonnes) from the one region model. The shaded area indicates the approximate 95% confidence intervals.
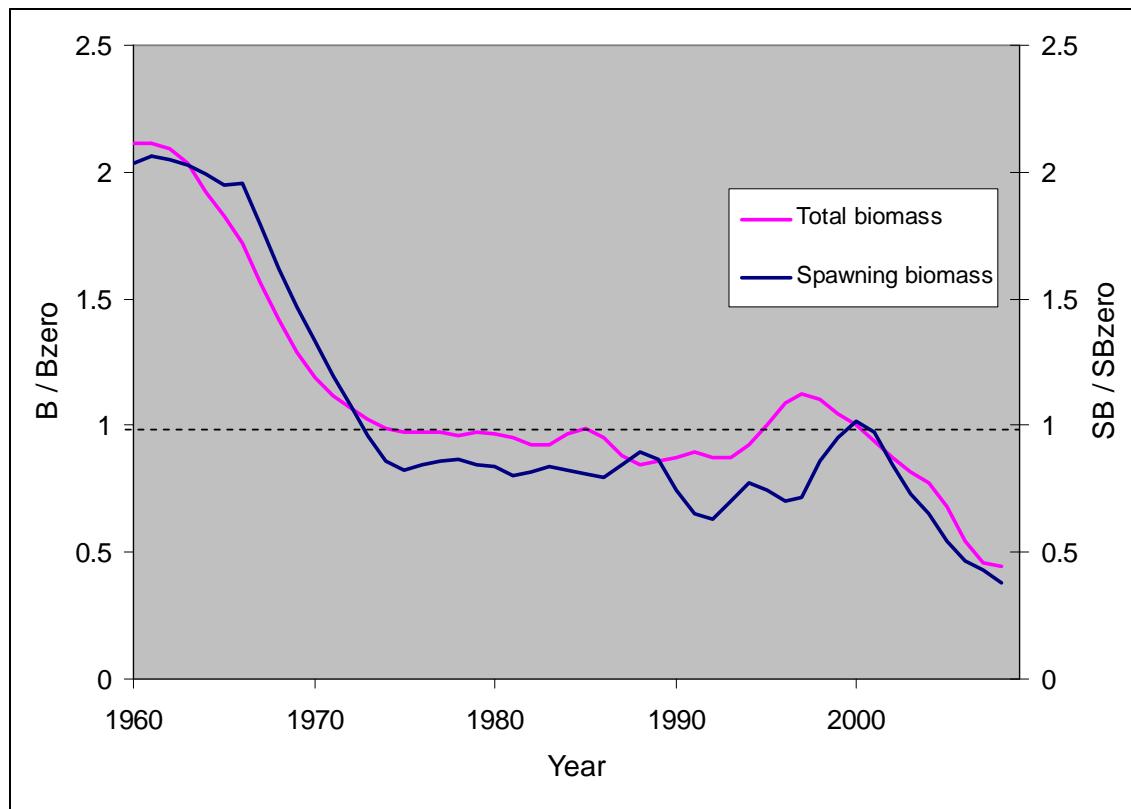
Figure 34: Time series of the ratios B / B_0 and SB / SB_0. Initial biomasses are estimated to be well above equilibrium unfished levels.
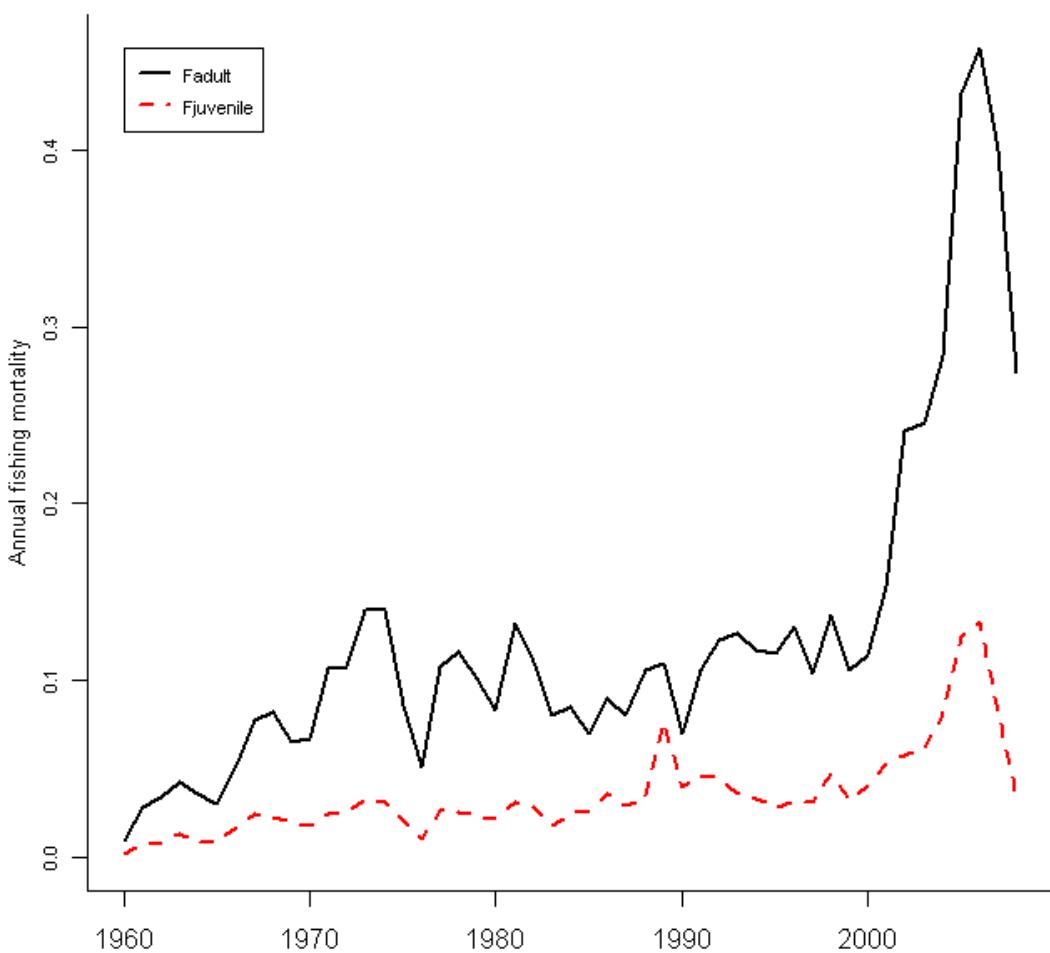
Figure 35: Annual estimates of fishing mortality for juvenile and adult south Pacific albacore.
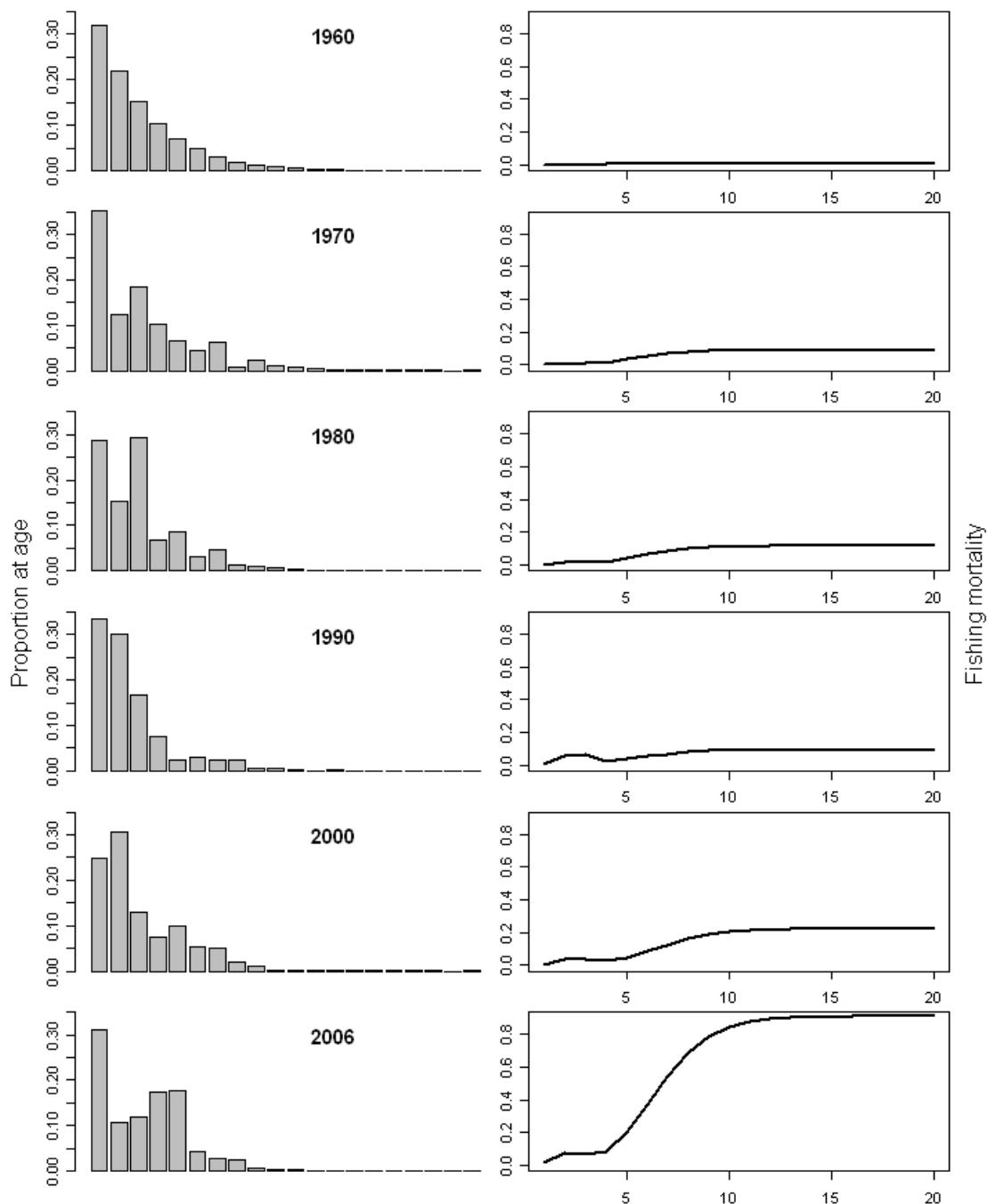
Figure 36: Estimated proportion at age (left) and mortality at age (right) by year at decade intervals, and in 2006.
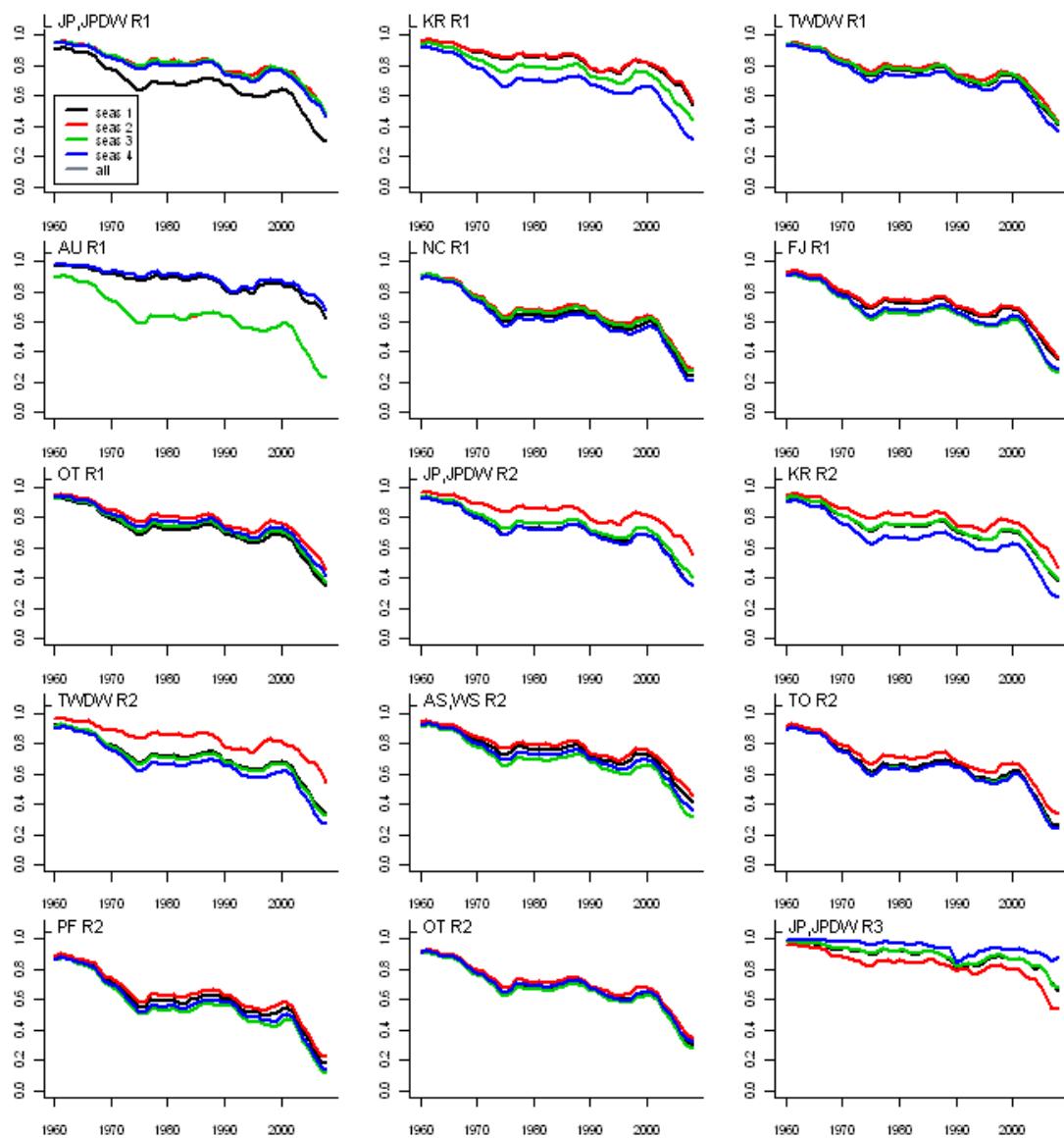
Figure 37a: The ratio between the level of exploitable biomass for individual fisheries and the level of exploitable biomass predicted in the absence of fishing.
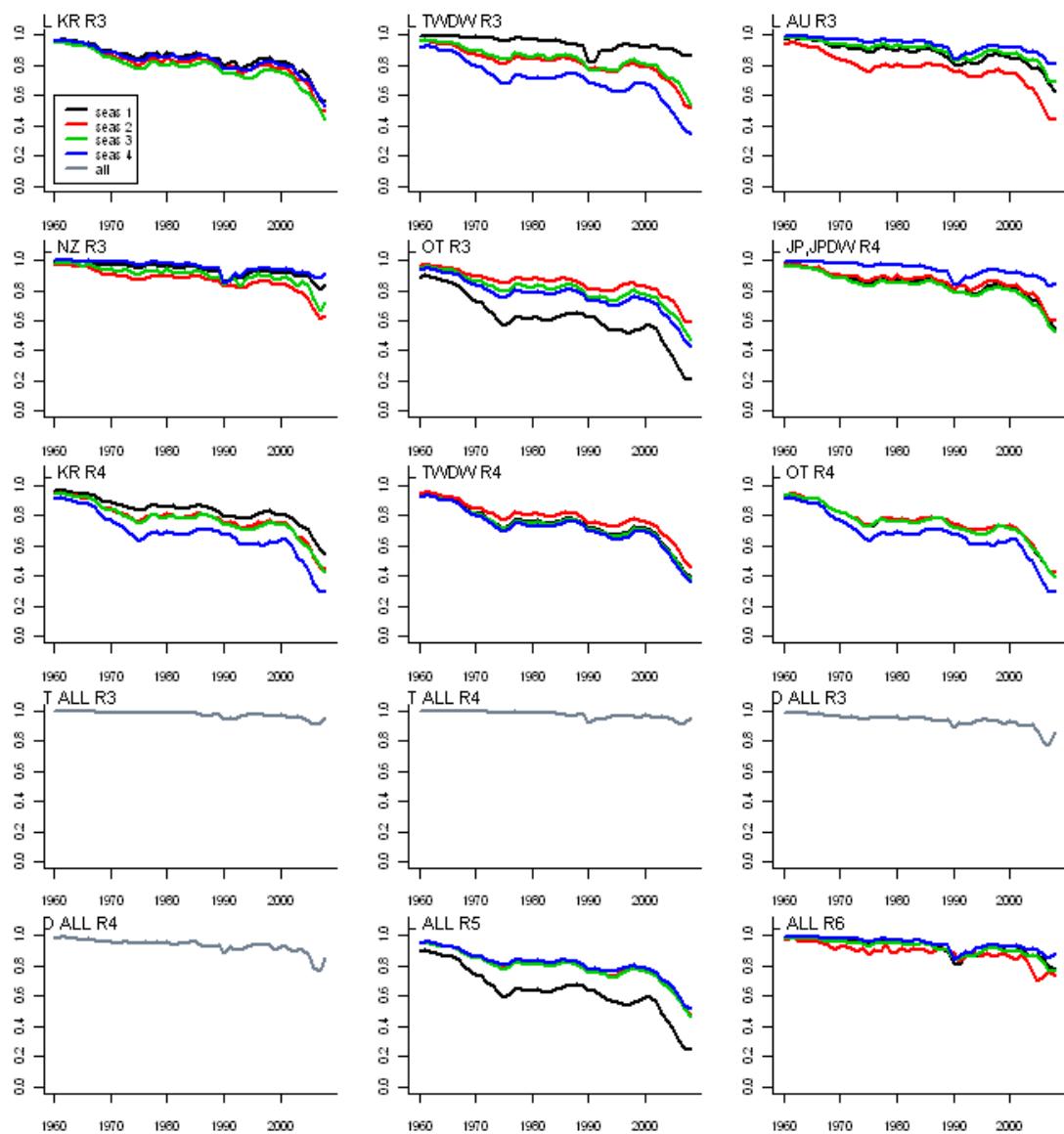
Figure 37b. Continued.
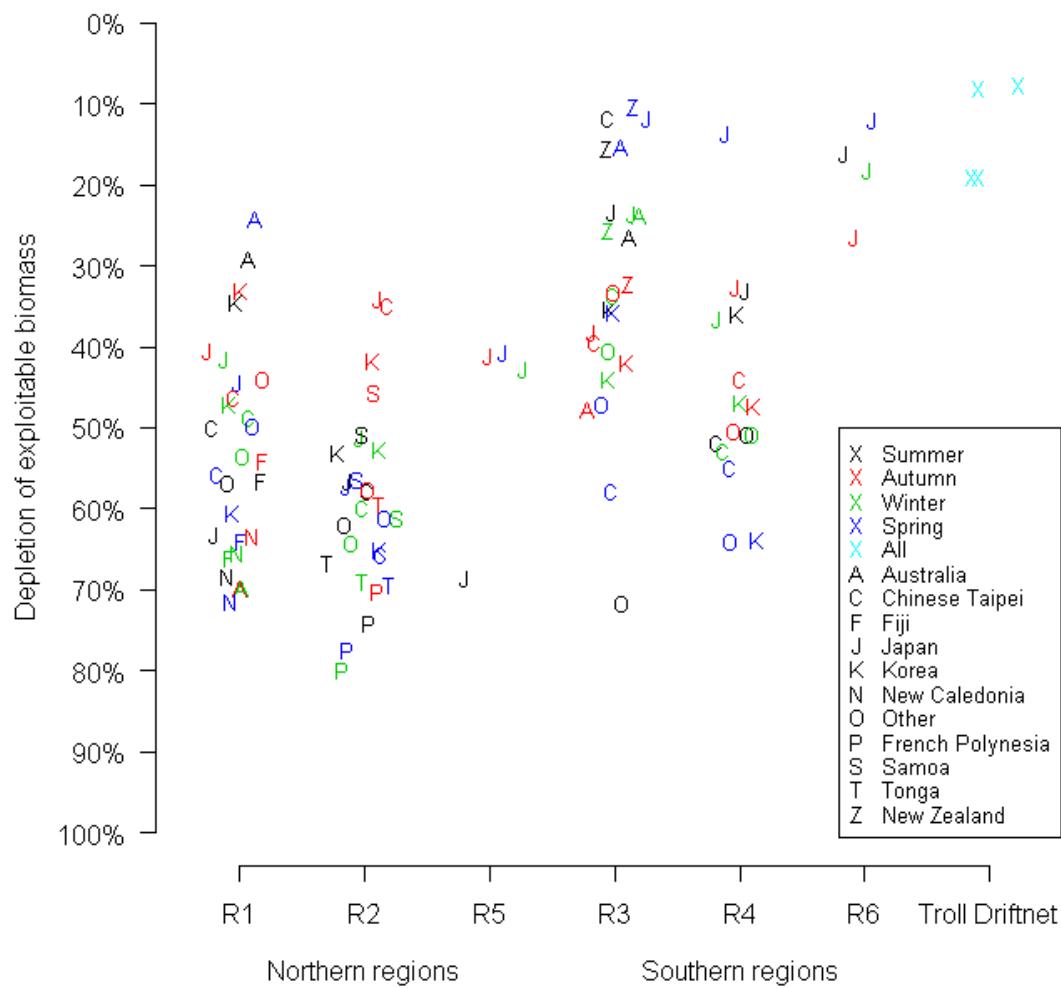
Figure 38: Average depletion (due to all fishing) of exploitable biomass by fishery, for the period 2004-2006, by fishery. Fisheries are coloured by season, and labelled according to flag.
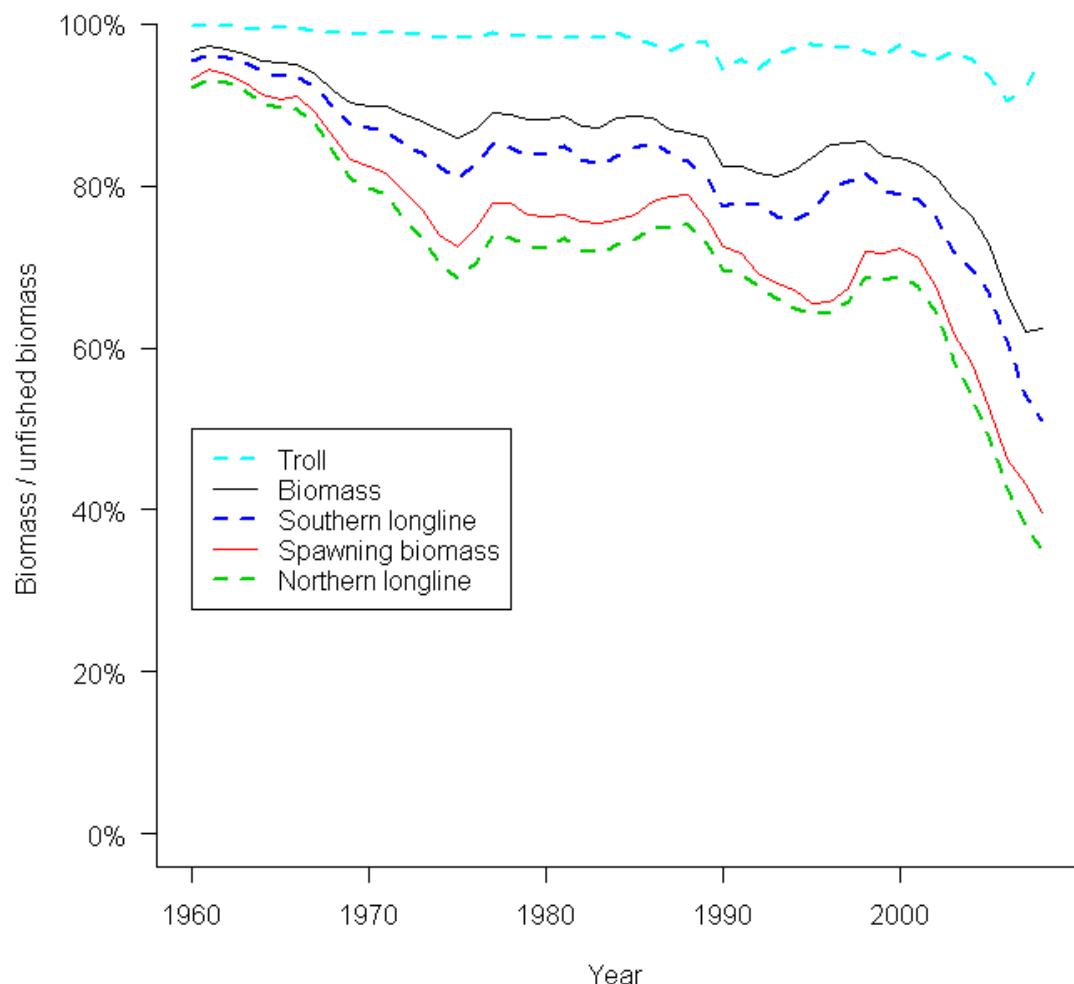
Figure 39: Decline in biomass due to the impact of fishing mortality, for exploitable biomass in the troll, southern longline, and northern longline fisheries, for total biomass and for spawning biomass.
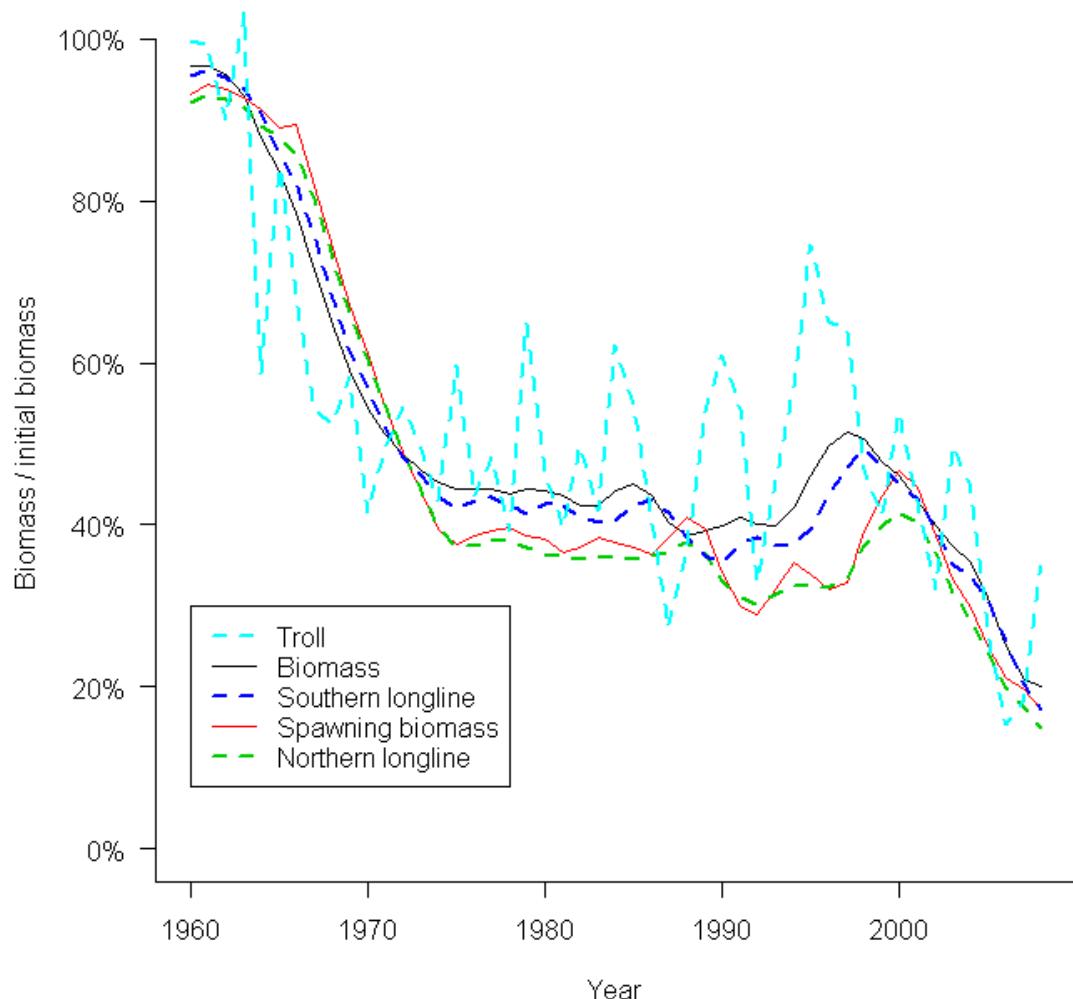
Figure 40: Decline in biomass relative to initial biomass B₀, for exploitable biomass in the troll, southern longline, and northern longline fisheries, for total biomass, and for spawning biomass.
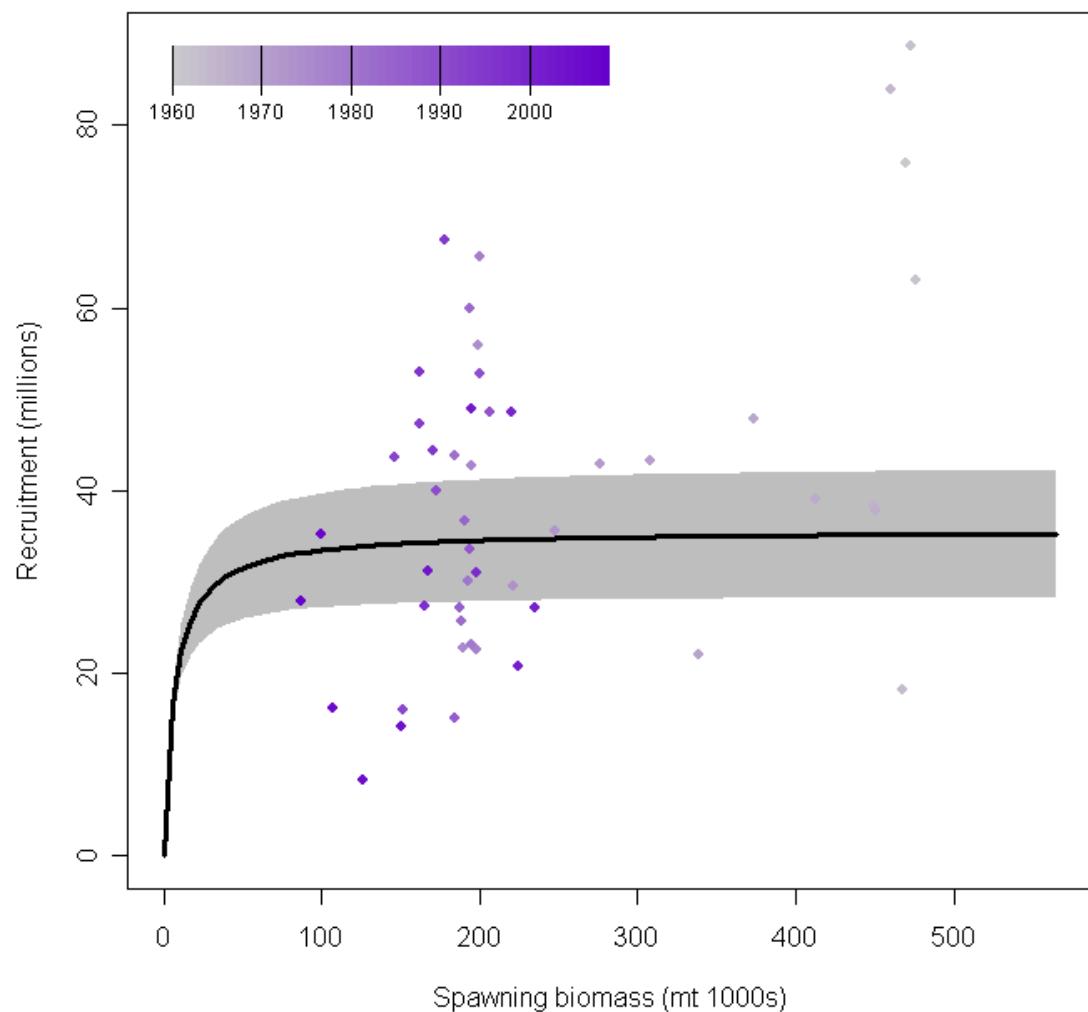
Figure 41. Spawning biomass − recruitment estimates and the fitted Beverton and Holt stock-recruitment relationship (SRR).
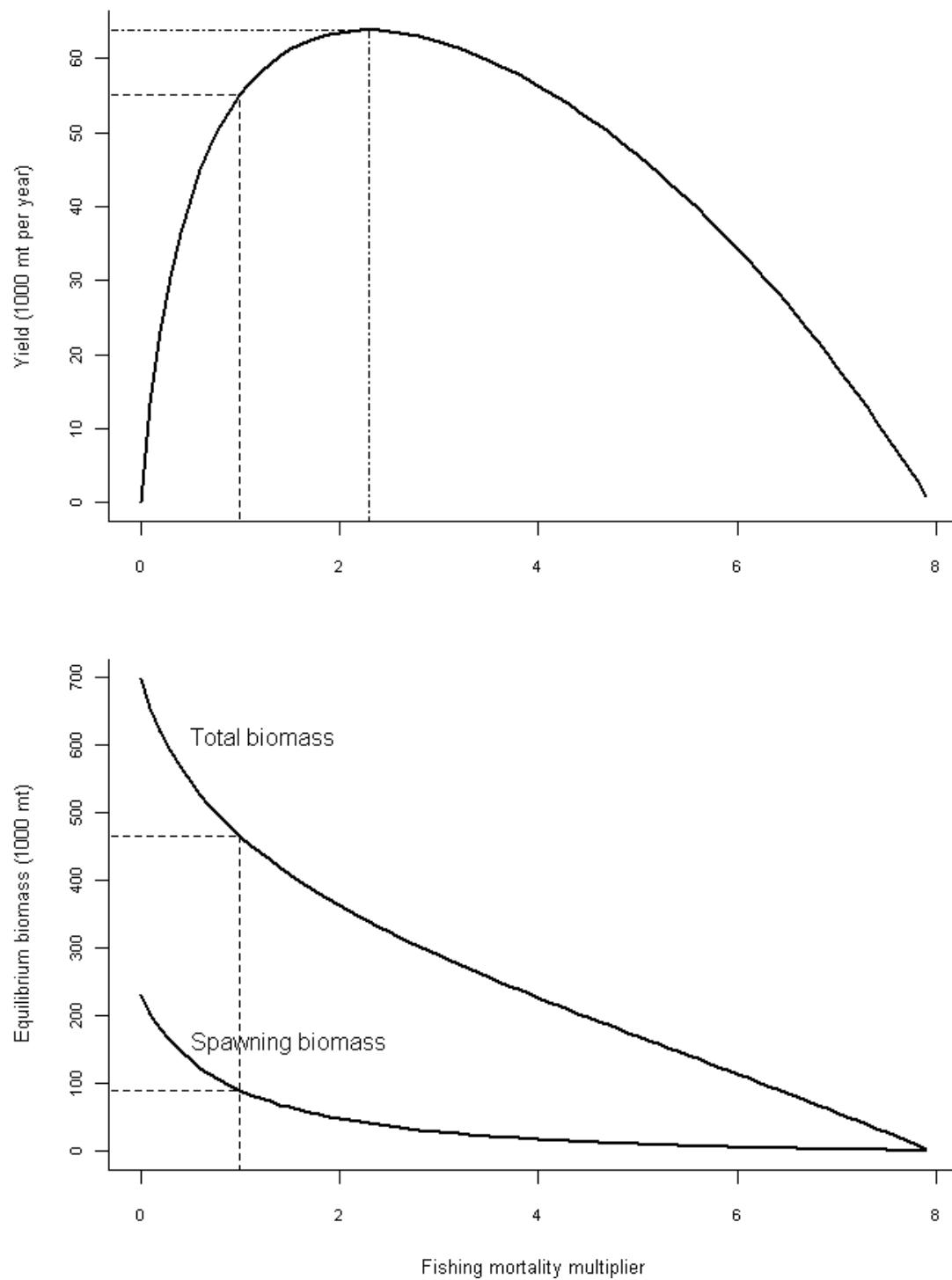
Figure 42: Yield, equilibrium biomass and equilibrium spawning biomass as a function of fishing mortality multiplier. In the top figure the dotted lines indicate equilibrium yield at the current fishing mortality, and maximum sustainable yield. In the lower figure the dotted lines represent equilibrium values of spawning biomass and total biomass at current fishing mortality.
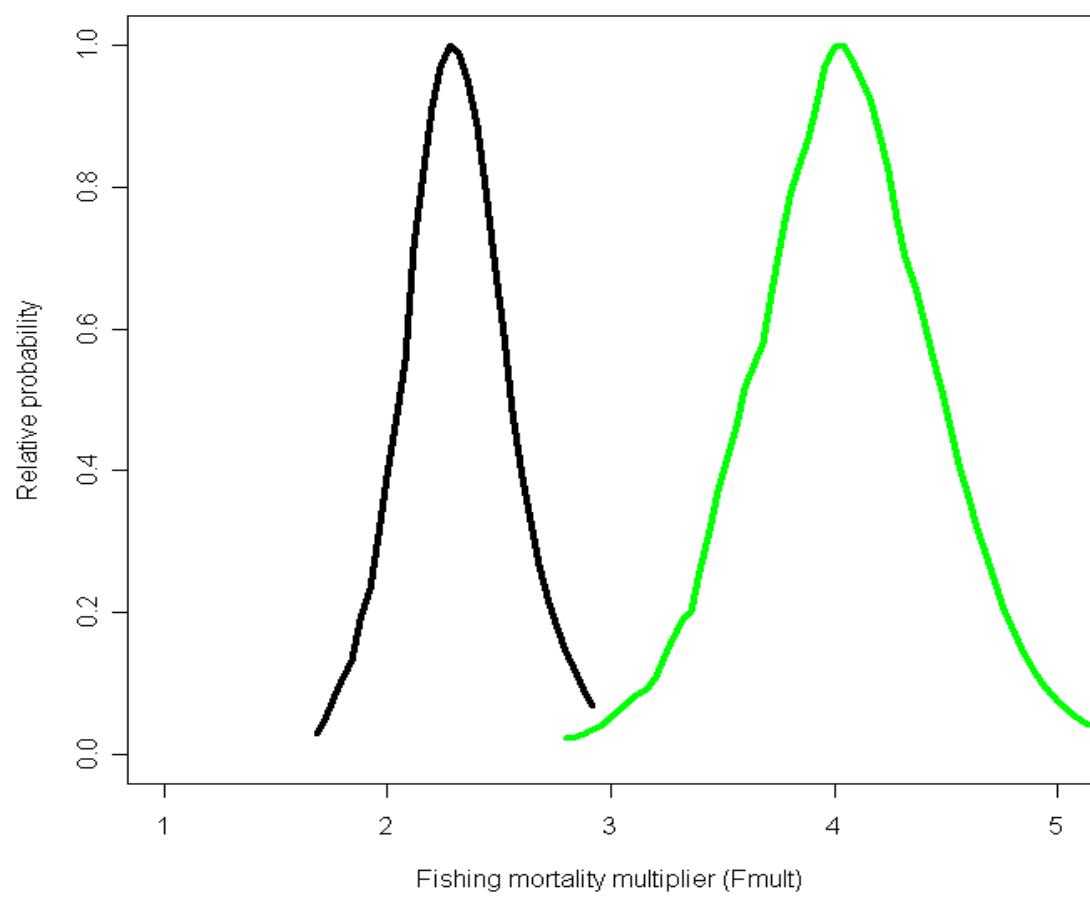
Figure 43: Likelihood profiles indicating parameter uncertainty in the fishing mortality multplier for the base case (black) and the model with less flexible effort deviates (green)
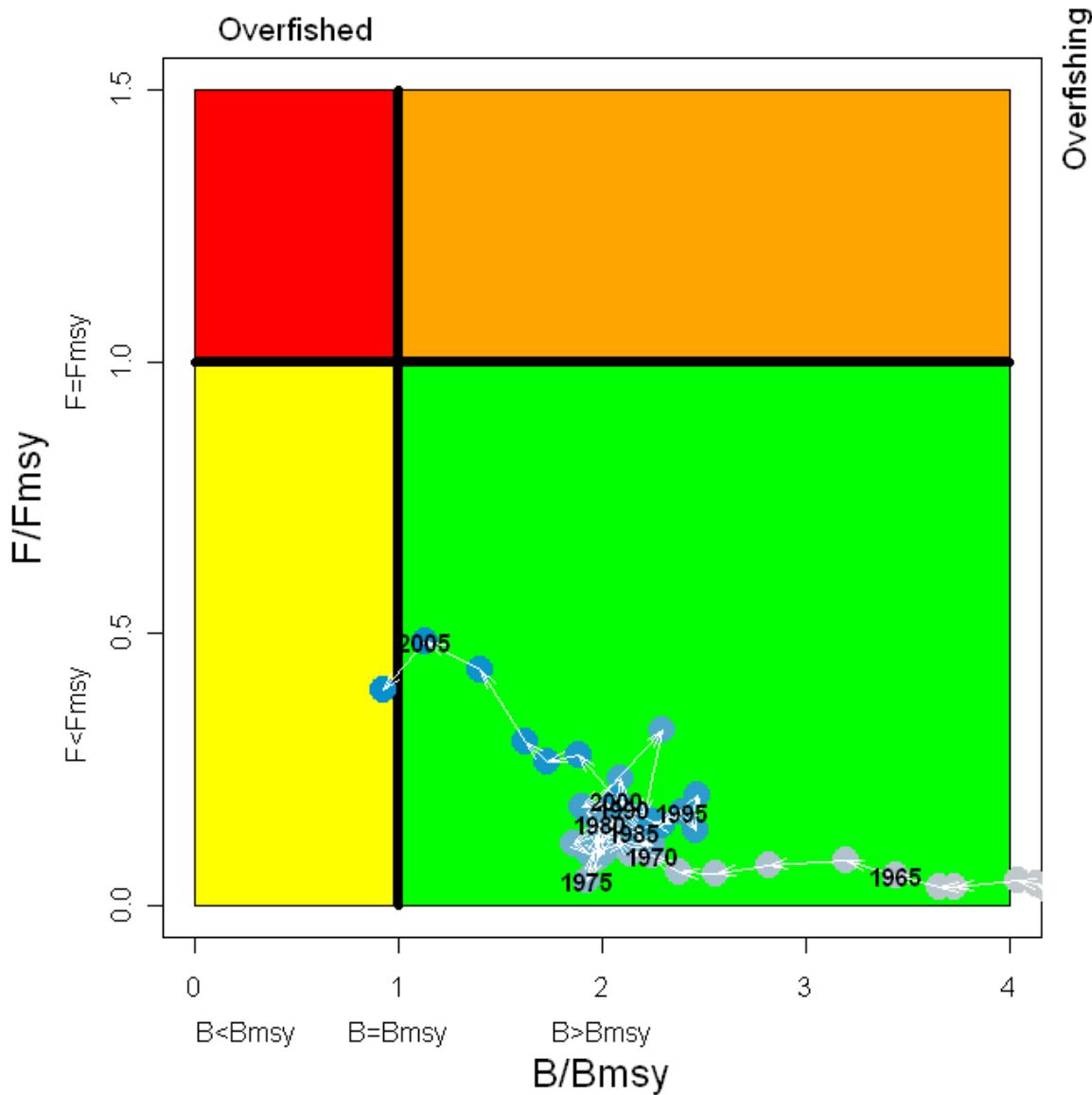
Figure 44: Temporal trend in annual stock status, relative to BMSY (x-axis) and FMSY (y-axis) reference points, for the model period (1960–2006) for the four main alternative models. The colour of the points is graduated from pale blue (1960) to blue (2006) and the points are labelled at 5-year intervals. The last year of the model (2007) is excluded as it is highly uncertain.
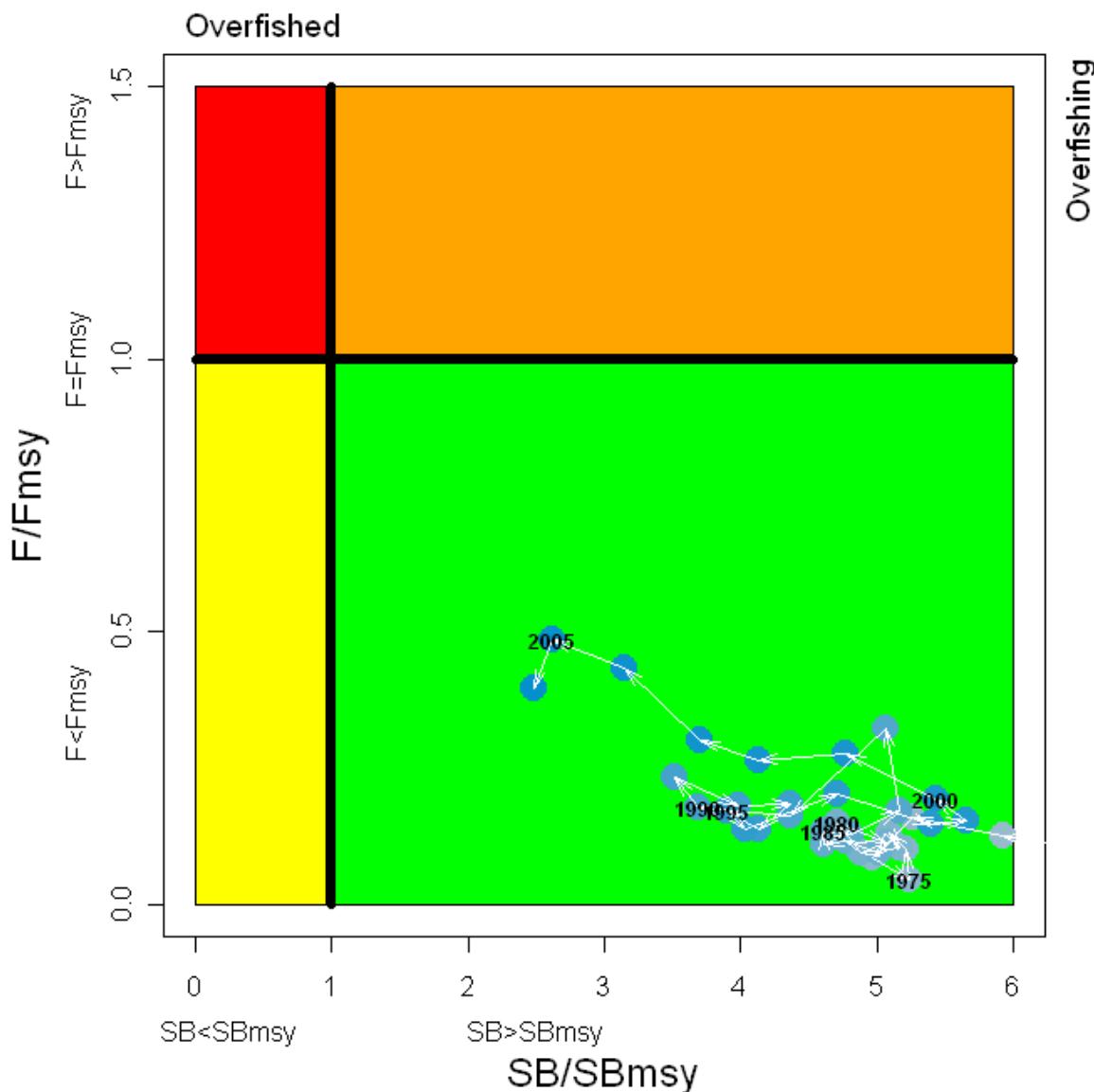
Figure 45: Temporal trend in annual stock status, relative to SBMSY (x-axis) and FMSY (y-axis) reference points, for the model period (1960–2006) for the four main alternative models. The colour of the points is graduated from pale blue (1960) to blue (2006) and the points are labelled at 5-year intervals. The last year of the model (2007) is excluded as it is highly uncertain.

.
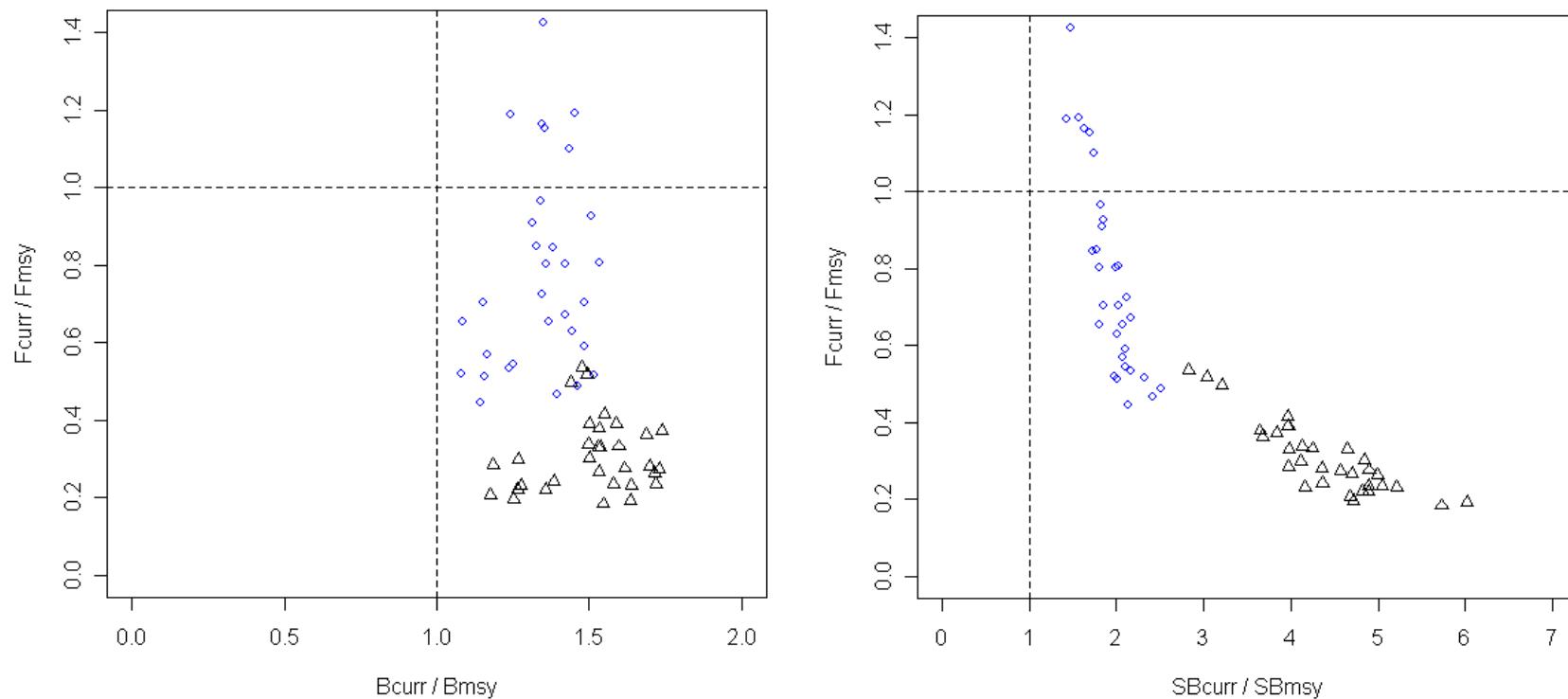
Figure 46: Scatter plots of values estimated under a grid of scenarios for steepness, the growth curve, effort creep, start year, time split, and the weight given to the length frequency data. Response variables are a) $F_{2004\text{-}2006}$ / F_{MSY} versus the biomass depletion ratio $B_{2004\text{-}2006}$ / B_{MSY}, and b) $F_{2004\text{-}2006}$ / F_{MSY} versus the spawning biomass depletion ratio $SB_{2004\text{-}2006}$ / SB_{MSY}. Black triangles are for steepness of 0.95 and blue circles are for steepness of 0.75.
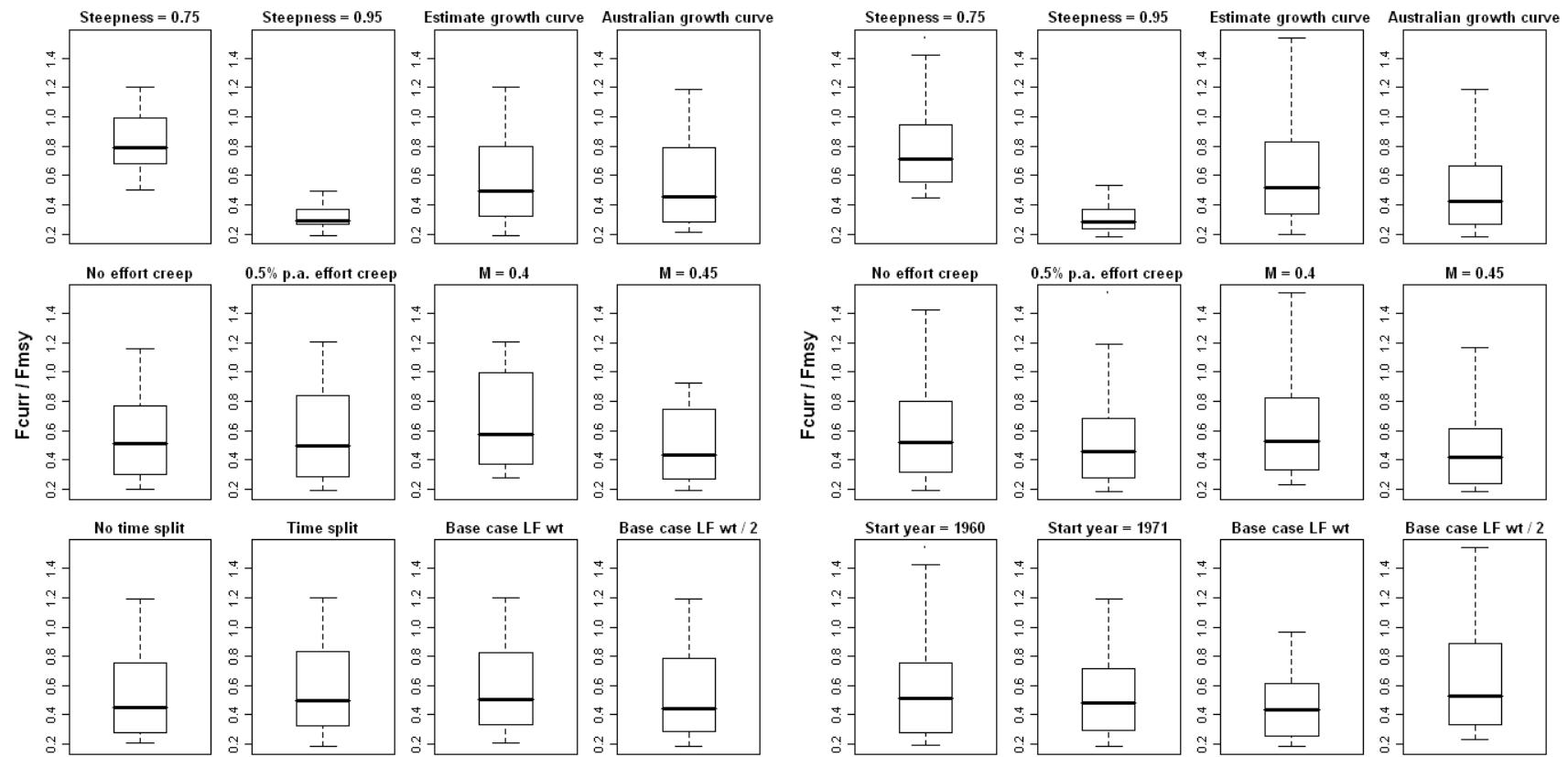
Figure 47: Box and whisker plots indicating the distribution of the fishing mortality ratio $F_{2004\text{-}2006}$ / F_{MSY} estimated under a grid of scenarios for steepness, the growth curve, effort creep, start year, time split, and the weight given to the length frequency data. Plots on the left are from runs in which the start year was uniformly 1960. Plots on the right are from scenarios in which there were no time splits.
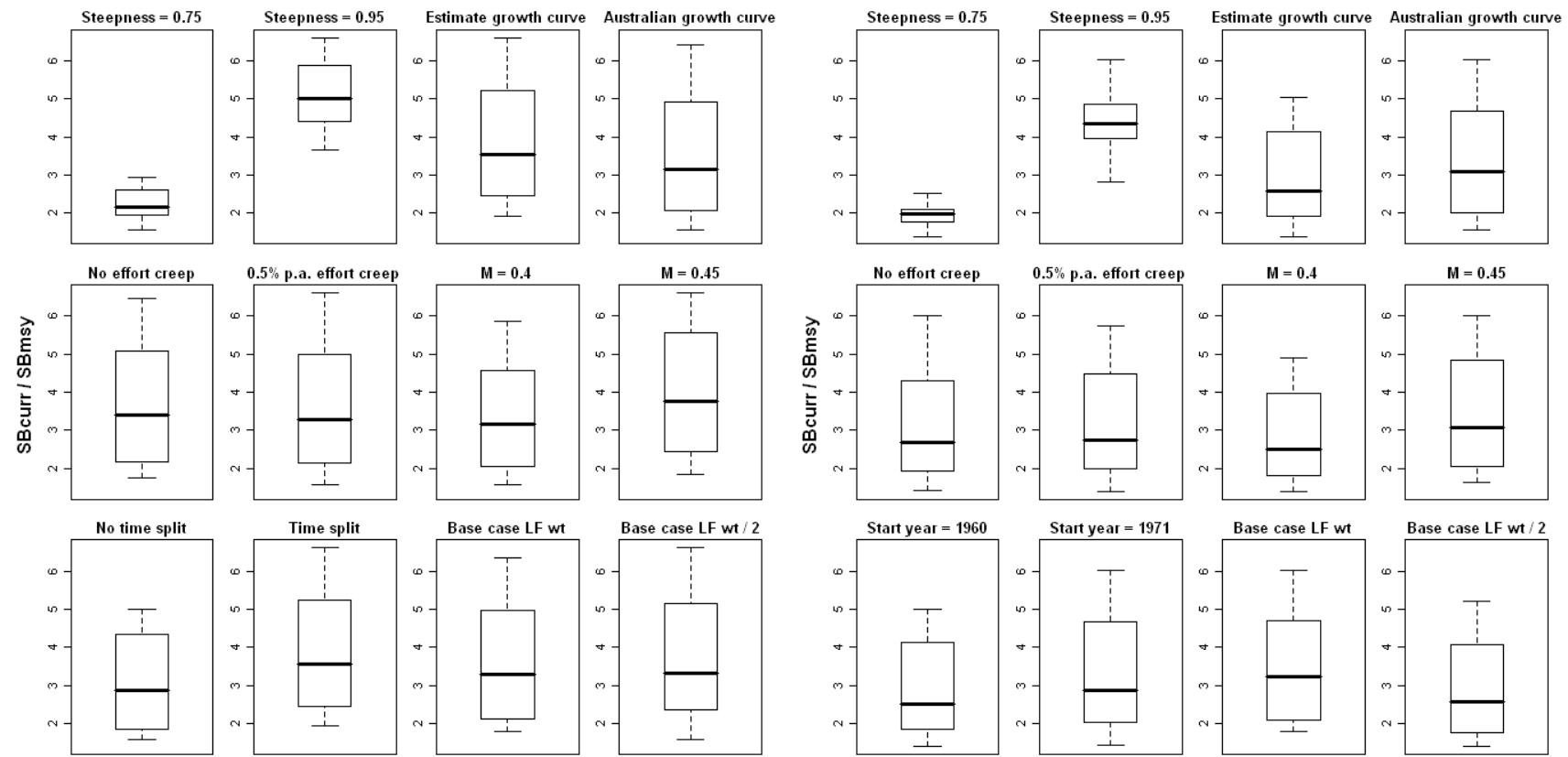
Figure 48: Box and whisker plots indicating the distribution of the spawning biomass depletion ratio $SB_{2004\text{-}2006}$ / SB_{MSY} estimated under a grid of scenarios for steepness, the growth curve, effort creep, start year, time split, and the weight given to the length frequency data. Plots on the left are from runs in which the start year was uniformly 1960. Plots on the right are from scenarios in which there were no time splits.
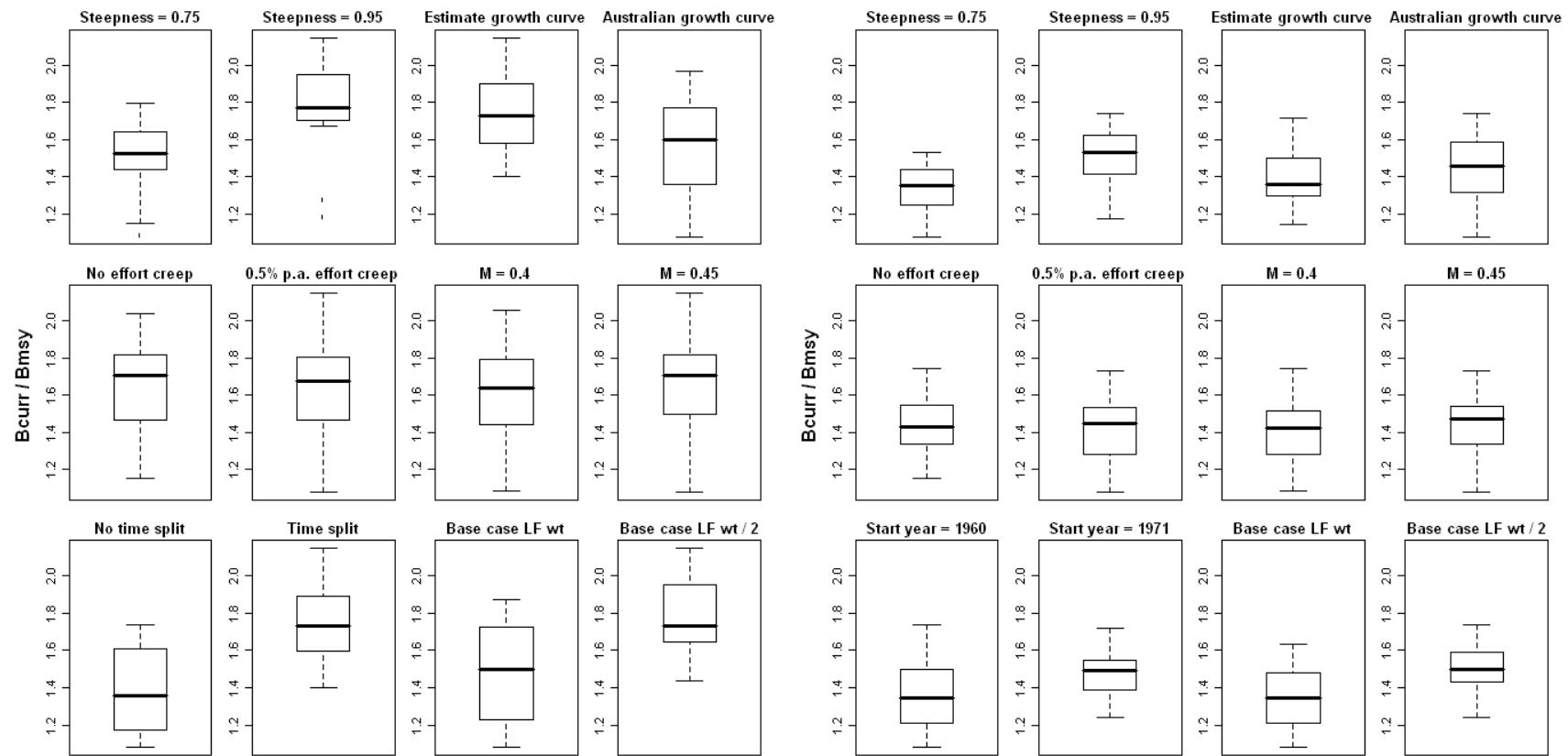
Figure 49: Box and whisker plots indicating the distribution of the biomass depletion ratio $B_{2004\text{-}2006}$ / B_{MSY} estimated under a grid of scenarios for steepness, the growth curve, effort creep, start year, time split, and the weight given to the length frequency data. Plots on the left are from runs in which the start year was uniformly 1960. Plots on the right are from scenarios in which there were no time splits.

12 Appendix 1: Doitall file

SOUTH PACIFIC ALBACORE ANALYSIS
1952-2007 data (by quarter **)
#
Definition of regions
#
Region 1: 0-25S, 140E-180
Region 2: 0-25S, 180-110W
Region 3: 25S-50S, 140E-180
Region 4: 25S-50S, 180-110W
Region 5: 0-25S, 110-70W
Region 6: 25S-50S, 110-70W
#
Definition of fisheries
#
Fishery Gear Nation   Region
Fishery Gear Nation   Region
1   L   JP   1
2   L   JP   1
3   L   JP   1
4   L   JP   1
5   L   KR   1
6   L   KR   1
7   L   KR   1
8   L   KR   1
9   L   TW   1
10   L   TW   1
11   L   TW   1
12   L   TW   1
13   L   AU   1
14   L   AU   1
15   L   AU   1
16   L   AU   1
17   L   NC   1
18   L   NC   1
19   L   NC   1
20   L   NC   1
21   L   FJ   1
22   L   FJ   1
23   L   FJ   1
24   L   FJ   1
25   L   OT   1
26   L   OT   1
27   L   OT   1
28   L   OT   1
29   L   JP   2
30   L   JP   2
31   L   JP   2
32   L   JP   2
33   L   KR   2

34   L   KR   2
35   L   KR   2
36   L   KR   2
37   L   TW   2
38   L   TW   2
39   L   TW   2
40   L   TW   2
41   L   AS,WS   2
42   L   AS,WS   2
43   L   AS,WS   2
44   L   AS,WS   2
45   L   TO   2
46   L   TO   2
47   L   TO   2
48   L   TO   2
49   L   PF   2
50   L   PF   2
51   L   PF   2
52   L   PF   2
53   L   OT   2
54   L   OT   2
55   L   OT   2
56   L   OT   2
57   L   JP   3
58   L   JP   3
59   L   JP   3
60   L   JP   3
61   L   KR   3
62   L   KR   3
63   L   KR   3
64   L   KR   3
65   L   TW   3
66   L   TW   3
67   L   TW   3
68   L   TW   3
69   L   AU   3
70   L   AU   3
71   L   AU   3
72   L   AU   3
73   L   NZ   3
74   L   NZ   3
75   L   NZ   3
76   L   NZ   3
77   L   OT   3
78   L   OT   3
79   L   OT   3
80   L   OT   3
81   L   JP   4
82   L   JP   4
83   L   JP   4
84   L   JP   4
85   L   KR   4

```
#    86   L    KR    4                    2 95 3
#    87   L    KR    4                  # 2 94 1      # equilibrium calculation of initial
#    88   L    KR    4                  population based on ??
#    89   L    TW    4                  # 2 95 10     # uses average Z over 1st 10 years?
#    90   L    TW    4                  qtrs?
#    91   L    TW    4                   -999 26 2  # length-dependent selectivity
#    92   L    TW    4                   -999 33 1   # estimate tag-reporting rate
#    93   L    OT    4                   1 33 90     # maximum tag reporting rate is 0.9
#    94   L    OT    4                   -999 35 1   # penalty on reporting rate, i.e. prior
#    95   L    OT    4                  is uninformative
#    96   L    OT    4                   -999 36 10  # prior for reporting rate is 0.1
#    97   T    ALL   3                   -999 13 -10 # sets penalty weights for effort
#    98   T    ALL   4                  devs
#    99   D    ALL   3                   -999 15 50  # sets penalty weights for q devs
#    100   D    ALL   4                  -9999 1 4   # sets first tag flag to 4 (no. mixing
#    101   L    ALL   5                  periods) for all
#    102   L    ALL   5                  #          tag release sets (** was 1 before)
#    103   L    ALL   5                  # grouping of fisheries for tag reporting rate
#    104   L    ALL   5                  -1 34 1
#    105   L    ALL   6                  -2 34 1
#    106   L    ALL   6                  -3 34 1
#    107   L    ALL   6                  -4 34 1
#    108   L    ALL   6                  -5 34 2
#        109    T    ALL   3             -6 34 2
#        noGLM                           -7 34 2
#        110   L    JP   4 ssn1 - noGLM  -8 34 2
#        111   L    JP   4 ssn2 - noGLM  -9 34 3
#        112   L    JP   4 ssn3 - noGLM  -10 34 3
#        113   L    JP   4 ssn4 - noGLM  -11 34 3
#        114   L    KR   4 ssn2 - noGLM  -12 34 3
#        115   L    JP   1 ssn3 - noGLM  -13 34 4
#        116   L    JP   1 ssn4 - noGLM  -14 34 4
#        117   L    JP   3 ssn2 - noGLM  -15 34 4
#        118   L    JP   3 ssn3 - noGLM  -16 34 4
#        119   L    JP   3 ssn4 - noGLM  -17 34 5
#                                        -18 34 5
# -----------------------                -19 34 5
# Create initial par file                -20 34 5
# -----------------------                -21 34 6
 ./mfclo32 alb.frq alb.ini 00.par -makepar  -22 34 6
# -----------------------                -23 34 6
# Initial fit conditions                 -24 34 6
# -----------------------                -25 34 7
#if [ ! -f 01.par ]; then                -26 34 7
 ./mfclo32 alb.frq 00.par 01.par -file -  -27 34 7
<<PHASE1                                 -28 34 7
 2 32 1                                  -29 34 1
 1 32 6     # sets "no vonB" initial estimation  -30 34 1
 1 111 2    # likelihood function for tags =  -31 34 1
poisson                                  -32 34 1
 1 141 3    # likelihood function for LF data =  -33 34 2
normal                                   -34 34 2
 2 57 1     # set no. of recruitments per year to 1  -35 34 2
 2 93 1     # set no. of recruitments per year to 1  -36 34 2
 2 69 1     # sets generic movement option  -37 34 3
  2 94 2                                 -38 34 3
```

-39 34 3
-40 34 3
-41 34 8
-42 34 8
-43 34 8
-44 34 8
-45 34 9
-46 34 9
-47 34 9
-48 34 9
-49 34 10
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-94 34 14

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-99 34 17
-100 34 18
-101 34 1
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-103 34 1
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-105 34 1
-106 34 1
-107 34 1
-108 34 1
sets non-decreasing selectivity for longline
fisheries
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-103 16 0
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-105 16 0
-106 16 0
-107 16 0
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sets zero selectivity for age classes 19 and 20
in troll fisheries
-97 16 2
-98 16 2
initial grouping of fisheries with common
selectivity
now separate Australia in 1 and 3 and NC
fishery
common for DN fisheries
 -1 24 1
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-107 24 106
-108 24 107
#use cubic spline for selectivity
 -999 57 3
 -999 61 4 #number of parameters in cubic spline
#catchability groupings
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-52 60 52	-108 60 108
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-56 60 56	-109 60 109
-57 60 57	-109 13 -1
-58 60 58	-110 16 0
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-61 60 61	-110 13 -1
-62 60 62	-111 16 0
-63 60 63	-111 29 111
-64 60 64	-111 60 111
-65 60 65	-111 13 -1
-66 60 66	-112 16 0
-67 60 67	-112 29 112
-68 60 68	-112 60 112
-69 60 69	-112 13 -1
-70 60 70	-113 16 0
-71 60 71	-113 29 113
-72 60 72	-113 60 113
-73 60 73	-113 13 -1
-74 60 74	-114 16 0
-75 60 75	-114 29 114
-76 60 76	-114 60 114
-77 60 77	-114 13 -1
-78 60 78	-115 16 0
-79 60 79	-115 29 115
-80 60 80	-115 60 115
-81 60 81	-115 13 -1
-82 60 82	-116 16 0
-83 60 83	-116 29 116
-84 60 84	-116 60 116
-85 60 85	-116 13 -1
-86 60 86	-117 16 0
-87 60 87	-117 29 117
-88 60 88	-117 60 117
-89 60 89	-117 13 -1
-90 60 90	-118 16 0
-91 60 91	-118 29 118
-92 60 92	-118 60 118
-93 60 93	-118 13 -1
-94 60 94	-119 16 0
-95 60 95	-119 29 119
-96 60 96	-119 60 119
-97 60 97	-119 13 -1
-98 60 98	-109 24 97
-99 60 99	-110 24 81

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 -111 24 82                                            -32 10 0
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 -113 24 84                                            -34 10 0
 -114 24 86                                            -35 10 0
 -115 24 3                                             -36 10 0
 -116 24 4                                             -37 10 0
 -117 24 58                                            -38 10 0
 -118 24 59                                            -39 10 0
 -119 24 60                                            -40 10 0
PHASE1                                                 -57 10 0
recruitmentConstraints 01.par 0.9                      -58 10 0
 ./mfclo32 alb.frq 01.par 02.par -file -               -59 10 0
<<PHASE2                                               -60 10 0
 1 149 100                                             -61 10 0
  1 13 0                                               -62 10 0
 -999 3 19   # 1st age class of 20 where               -63 10 0
selectivity held fixed                                 -64 10 0
 -999 4 2    # turn on effort dev estimation           -65 10 0
 1 189 1     # write graph.frq file (LF observed       -66 10 0
and predicted)                                         -67 10 0
 1 190 1     # write plot.rep                          -68 10 0
 1 1 100     # no. function evaluations                -81 10 0
PHASE2                                                 -82 10 0
#                                                      -83 10 0
 ./mfclo32 alb.frq 02.par 03.par -file -               -84 10 0
<<PHASE3                                               -85 10 0
 1 16 1      # estimate length dependent SD            -86 10 0
 1 1 100     # no. function evaluations                -87 10 0
 1 50 -6     # sets convergence criterion to 1E-6      -88 10 0
PHASE3                                                 -89 10 0
#                                                      -90 10 0
# estimate seasonal catchability                       -91 10 0
 ./mfclo32 alb.frq 03.par 04.par -file -               -92 10 0
<<PHASE4                                                -999 23 11
 -999 27 1   # estimate seasonal catchability           -999 15 1
PHASE4                                                 1 1 500     # no. function evaluations
#                                                      1 50 -6     # sets convergence criterion to 1E-6
# estimate catchability time series                     -97 10 0
 ./mfclo32 alb.frq 04.par 05.par -file -               PHASE5
<<PHASE5                                               #
 -999 10 1   # estimate time-series catchability        ./mfclo32 alb.frq 05.par 06.par -file -
-1 10 0                                                <<PHASE6
-2 10 0                                                 2 82 40     # prior for M is 40/100
-3 10 0                                                 2 84 0      # no penalty for prior
-4 10 0                                                  2 33 0
-5 10 0                                                 1 1 100     # no. function evaluations
-6 10 0                                                 1 50 -6     # sets convergence criterion to 1E-6
-7 10 0                                                PHASE6
-8 10 0                                                #
-9 10 0                                                 ./mfclo32 alb.frq 06.par 07.par -file -
-10 10 0                                               <<PHASE7
-11 10 0                                                 1 14 1
-12 10 0                                                1 1 100     # no. function evaluations
-29 10 0                                                1 50 -6     # sets convergence criterion to 1E-6
-30 10 0                                                 -999 49 20
-31 10 0                                                 1 12 1
```

```
 1 13 1
PHASE7
#
 ./mfclo32 alb.frq 07.par 08.par -file -
<<PHASE8
 -999 55 1  # activate 'no fishing'
 2 35 10    # set effort deviate limits to +-10
 2 193 1    # activate 'no fishing'
 2 145 2    # activates SRR with penalty 2 (same
as yft)
 2 146 1    # estimate SRR parameter
 2 163 0    # use steepness
 2 162 0    # don't estimate steepness
 2 147 1    # lag between spawning and
recruitment
 2 148 4    # no. years for averaging F (same as
yft)
 2 155 1    # but omits the last year
#  2 153 100  # a in beta prior for steepness
#  2 154 20   # b in beta prior for steepness
 1 149 0    # recr dev pen to 0
 1 1 2000
 2 35 10
PHASE8
```