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STOCK ASSESSMENT OF ALBACORE TUNA IN THE SOUTH PACIFIC OCEAN

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Executive Summary

This paper presents the current stock assessment of albacore tuna (*Thunnus alalunga*) in the South Pacific Ocean. The assessment uses the stock assessment model and computer software known as MULTIFAN-CL (or MFCL).

Since the last assessment, many of the model's underlying structural assumptions have been reviewed, with a focus on providing reliable estimates of population dynamics. This is a pre-requisite for providing useful management advice. Major changes to model data inputs and structure in the base case include:

An update of catch, effort, and size data to mid-2008; revised CPUE from a GLM for distant water fishing nation (DWFN) longline fisheries; time-dependent variance in CPUE; changes to growth modelling; monthly data aggregation for troll fisheries; model timing changed to mid-year; time splits in longline selectivity and first age bias in troll selectivity; use of 0.75 rather than 0.9 for steepness; and catchability decline estimated for the initial stages of the fishery.

These changes have resulted in a more realistic and credible model which fits the data better. The problem with bias in the CPUE series that result from switches in targeting and which were identified in 2008 appears to have been largely resolved. The conflict between information in the CPUE and the longline length frequency data remains, but its effects have been reduced. The new growth estimates fit the troll fishery length frequency data well and are close to estimates derived from otoliths.

We offer the following conclusions:

Stock status

- Levels of stock size and *MSY* appear more realistic than in the 2008 assessment, because many sources of potential bias have been removed.
- However, moderate uncertainty remains about biomass and fishing mortality levels.
- Models that down-weight the length frequency data (in order to rely on the index of abundance from the CPUE data), tend to give lower biomass relative to B_{MSY}, and higher fishing mortality relative to F_{MSY}, throughout the time series.
- There is considerable uncertainty about the early biomass trend, but this has negligible effect on the management parameters, or advice to managers regarding the status of the stock (Table 5).
- Estimates of $F_{2005\text{-}2007}/F_{MSY}$ (from 0.1 to 0.5) and $SB_{2005\text{-}2007}$ / SB_{MSY} (from 1.7 to 4.9) are quite variable between model configurations, but all estimates indicate that overfishing is not occurring (i.e. $F_{2005\text{-}2007} < F_{MSY}$) and that the fishery is not in an overfished state (i.e. $SB_{2005\text{-}2007}$ is greater than SB_{MSY}.)
- Most of the variation in management parameters is attributable to the steepness of the stock recruitment relationship – something we have no information about. Alternative metrics such as the expected CPUE, relative to a target CPUE, may be both more relevant and more precise.
- There is no indication that current levels of catch are not sustainable in terms of recruitment overfishing, particularly given the age selectivity of the fisheries. However, current levels of fishing pressure appear to be affecting longline catch rates.

A number of potential research directions are suggested. These include:

- Thoroughly investigate the length frequency data in order to resolve the data conflicts which continue to affect the model, and may be biasing abundance estimates.

- Collaborate with scientists (and industry) from distant water fishing nations to develop better understanding of changes in fishing practices over time, which may affect estimates of catchability and selectivity.
- Investigate alternative reference points that may be more relevant and more precise.
- An integrated assessment of North and South Pacific albacore would be beneficial.
- Models with separate sub-populations by region should be explored further.

- Carry out biological research to provide better information for the growth curve, particularly growth differences between sexes, variation in length at age for the oldest fish, and the nature of regional variation in growth.
- Better information about appropriate model structure is needed, and growth and movement information would support this development. Electronic tagging work to determine fish movement patterns is desirable.

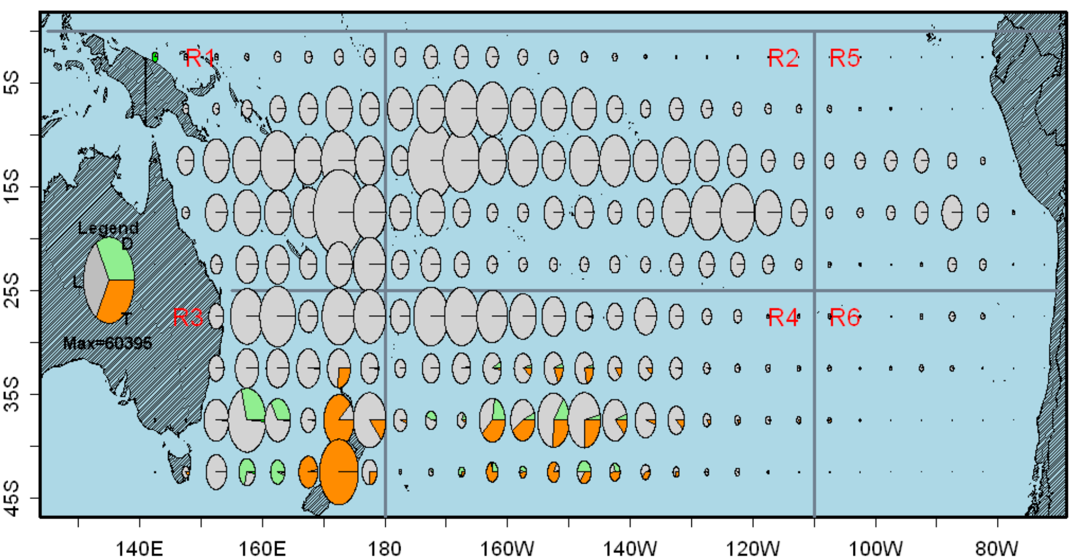

Figure 1: Map showing model regions 1 to 6, and the total catches (1960 to 2008) by 5^0 squares of latitude and longitude by the longline, troll, and driftnet fisheries.

1 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, which indicate the stock status and fishing impacts. 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 (*MSY*) ($B_{2005-2007}/\tilde{B}_{MSY}$) and recent fishing mortality to fishing mortality at *MSY* ($F_{2005-2007}/\tilde{F}_{MSY}$). The methodology used for the assessment is commonly known as MULTIFAN-CL (or MFCL) (Fournier *et al.* 1998; Hampton and Fournier 2001; Kleiber *et al.* 2006, http://www.multifan-cl.org). MFCL is a software program that implements a size-based, age- and spatially-structured population model. Model parameters are estimated by maximising an objective function, consisting of both likelihood (data) and prior information components.

2 Background

2.1 Biology

Albacore tuna comprise a discrete stock in the South Pacific (Murray 1994). Mature albacore — above a minimum fork length (FL) of about 80 cm — spawn in tropical and sub-tropical waters between latitudes 10°S and 25°S during the austral summer (Ramon and Bailey 1996). Juveniles are recruited to surface fisheries in New Zealand's coastal waters, and in the vicinity of the sub-tropical convergence zone (STCZ, at about 40°S) in the central Pacific, about one year later at a size of 45–50 cm FL.

From this region, albacore appear to gradually disperse to the north (Figure 2), but may migrate seasonally between tropical and sub-tropical waters. These seasonal migrations have been inferred from monthly trends in longline catch rates in subequatorial waters (Langley 2004). Catch rates in subequatorial waters peak during December–January and May–July, indicating that albacore migrate south during early summer, and north during winter. This movement tends to correspond with the seasonal shift in the 23–28° C sea surface temperature isotherm location.

Daily otolith growth increments indicate that initial growth is rapid, with albacore reaching 45–50 cm (FL) in their first year (Leroy and Lehodey 2004; Kerandel *et al.* 2006). Subsequent growth is slower, at approximately 10 cm per year from ages 2–4, declining thereafter (Labelle *et al.* 1993; Farley and Clear 2008). Maximum recorded length is about 120 cm (FL).

The natural mortality rate is believed to be between 0.2 and 0.5 per year, with significant numbers of fish reaching 10 years or more. Currently, the longest period at liberty for a recaptured tagged albacore in the South Pacific is 11 years.

2.2 Fisheries

Distant-water longline fleets of Japan, Korea and Chinese Taipei, and domestic longline fleets of several Pacific Island countries, catch adult albacore over a large proportion of their geographic range (Figure 3). The Chinese Taipei fleet in particular have targeted albacore consistently since the 1960s, though to a lesser extent since 2000. In recent years, the longline catch has increased considerably with the development (or expansion) of small-scale longline fisheries targeting albacore in several Pacific Island countries, notably American Samoa, Cook Islands, Fiji, French Polynesia, New Caledonia, Samoa and Tonga. A troll fishery for juvenile albacore has operated in New Zealand's 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 from December–April (Figure 5). Longline fisheries operate throughout the year, although there is a strong seasonal trend in the catch distribution, with the fishery operating in southern latitudes (south of 35° S) during late summer and autumn, moving northwards during winter (Figure 5).

After an initial period of small-scale fisheries development, annual catches of South Pacific albacore varied considerably and have recently been between about 60,000–70,000 mt (Figure 6). The longline fishery harvested most of the catch, about 25,000–30,000 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. Catches from the troll fishery are relatively small, generally 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 drift-netting.

3 Data compilation

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

3.1 Spatial stratification

The geographic area encompassed in the assessment is the Pacific Ocean south of the equator, from 140°E to 110°W (Figure 3). This area includes almost all of the albacore catch from the South Pacific. Previous stock assessments of South Pacific albacore have stratified this area into three latitudinal bands (Hampton and Fournier 2001; Labelle and Hampton 2003; Hampton 2002) in order 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°, and was based on a qualitative and statistical analysis (Helu 2004). The criterion for defining an individual stratum was consistency in seasonal and temporal trends in albacore catch rates from the main constituent longline fisheries within an area, while retaining the separation of the northern and southern areas to account for differences in the size of fish caught by longline fisheries. Consideration was also given to where the main domestic longline fisheries operated to simplify the application of assessment results to local-scale management of these fisheries.

For the 2008 assessment, two changes were made to the definitions of spatial strata. These strata are used to define individual fisheries (see Section 0). First, the latitudinal boundary at 30°S was moved north to 25°S, after examining length-frequency data (Langley and Hoyle 2008). Average length-frequencies between 25°S and 30°S tend to be smaller than those further north, and more similar to southern strata than northern strata. The model assumes the same selectivity throughout a fishery, so consistency in catch size compositions within time-area strata is desirable. The second change was that two additional strata were added to the area east of the previous boundary at 110°W. Catch from these strata (mainly from Japanese distant-water longline fisheries) was previously included in the model, but length-frequency data were not. Adding the additional strata allowed these length-frequency data to be included.

The present assessment maintained the same regional structure as in 2008, and used a single-model region, with the six spatial strata being used to define fisheries.

3.2 Temporal stratification

The time period covered by this assessment is 1960–2008. Within this period, data were compiled into quarters (Jan–Mar, Apr–Jun, Jul–Sep, Oct–Dec), apart from the troll fishery data, which were stratified by month. Data from 2008 are very limited, so for most purposes, inferences should focus on results up to 2007.

3.3 Definition of fisheries

MFCL requires all catch and effort to be allocated to "fisheries". 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 in order to capture the variability in albacore fishing operations.

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. Also, the fisheries began at different times and have exhibited different seasonal and temporal trends in catch rates. This additional stratification also increases the utility of the assessment by generating results that are relevant to the management of individual domestic fisheries.

This assessment maintained the changes to fishery structure made for the 2008 assessment. In summary, 30 fisheries were initially defined, consisting of 26 separate longline fisheries, two driftnet fisheries, and two troll fisheries (Table 1). The longline fisheries comprised: i) Japanese, Korean and Chinese Taipei longline fisheries in each of the four western and central regions (i.e. accounting for 12 fisheries), ii) domestic fleets of Fiji, French Polynesia, New Caledonia, New Zealand, Samoa and American Samoa combined, and Tonga (i.e. 6 fisheries), iii) Australia's domestic fishery in two regions (i.e. 2 fisheries), and iv) the remaining longline data from all six regions (i.e. 6 fisheries). 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 8.

Working from this initial model 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 four, by quarter. Second, temporal changes in selectivity were modelled by splitting fisheries into discrete time periods.

3.4 Catch and effort data

Catch and effort data were compiled according to the fisheries defined in Table 1. All catches were expressed in numbers of fish, with the exception of the driftnet fishery, where catches were expressed in weight (metric tonnes). For longline fisheries, effort was expressed in hundreds of hooks, while for troll and driftnet fisheries, the number of vessel days of fishing activity was used. In previous assessments, data were aggregated by quarterly temporal strata for all fisheries. For the current assessment, data for the troll fisheries in regions 3 and 4 was aggregated by month, in order to provide better length frequency information for estimating growth rates.

Data used in compiling catch and effort data were derived from a variety of sources (mainly logsheet data and monthly 5^0-square 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 Western and Central Pacific (WCPFC) Tuna Fishery Yearbook. Details of methods used in compiling the data are as follows. Time-series of CPUE for all fisheries are shown in Figure 10.

Japanese longline catch (fisheries JP LL 1-4). Catch and effort data have been provided by Japan's National Research Institute of Far Seas Fisheries (NRIFSF) by month and 5^0-square resolution for 1952–2007. 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 New Zealand-Japan joint-venture operations south of 30°S have been included in the Japanese longline fishery.

Korean longline catch (fisheries KR LL 1-4). Aggregated catch and effort data have been provided by Korea's National Fisheries Research and Development Institute (NFRDI). For 1962–1974, only total annual catches in weight have been provided. For 1975–2007, catch in numbers and effort by month and 5^0-square resolution have been provided. For 1962–1974, the temporal and spatial distribution of size composition 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 a monthly and 5^0-square resolution. These samples were also used to estimate catch in numbers and catch in weight. Aggregated data provided for the Korean distant-water longline fleet do not cover 100% of fishing activities (i.e. catch and effort). Therefore, Korean distant-water longline data have been raised — according to the proportion of the total Korean longline catch of target tuna species, as provided in the latest version of the Western and Central Pacific Fisheries Commission (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; instead, the annual coverage rate for the entire WCPFC Convention Area has been used to raise the data. Note that data for 1975 cover less than 10% of the total estimated catch and so have not been raised. Catches in numbers were estimated from average weights derived from available size composition samples, where catch in weight was not provided.

Chinese Taipei longline catch (fisheries TW LL 1-4). Catch (in number) and effort data for the Chinese Taipei distant-water longline fleet, by month and 5^0-square resolution, have been provided by Chinese Taipei (1967–2007). SPC's Oceanic Fisheries Programme (OFP) corrected the 1967–1993 data for landings, following the method used in Lawson (1997), while the 1994–1996 data were corrected for landings by Chinese Taipei's Overseas Fisheries Development Council (OFDC). Data for 2002, 2004, 2005, 2006, and 2007 cover the WCPFC Convention Area only, while the other years cover the South Pacific. For 1964–1966, only annual catch weight estimates are available. The monthly 5^0-square catch distributions in these years were estimated from 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. For distant-water longline fisheries, effective (or standardised) effort was calculated by dividing catch by estimates of standardised CPUE. CPUE indices were obtained from generalised linear modelling (GLM) (Bigelow and Hoyle 2009) of albacore fishery data held by SPC. Effort for quarters without CPUE estimates was defined as "missing". Time-series of CPUE for all fisheries are shown in Figure 10.

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

Domestic longline fleets (fisheries AU LL 1, NC LL 1, FJ LL 1, AS/WS LL 2, TO LL 2, PF LL 2, AU LL 3, NZ LL 3, and OTHER LL 1-4). Separate longline fisheries were defined for each of the main domestic longline fisheries operating in the South Pacific, specifically the domestic fleets of Fiji, French Polynesia, New Caledonia, New Zealand, Samoa and American Samoa combined, and Tonga, with Australia's domestic fishery apportioned between two regions. Logbook data submitted by these countries to OFP were aggregated into a monthly 5^0-square format, and raised to estimates of their total annual catches. Most of these fisheries began 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, Papua New Guinea, Solomon Islands, Vanuatu) — were compiled into separate fisheries for Regions 1–4. Catch and effort data reported from Regions 5 and 6 were added to data from distant-water longline fisheries in those regions.

New Zealand domestic troll (TROLL 3). Catch estimates in weight and effort by month and 5^0-square resolution 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 month, using the distribution of the later data. Operational catch and effort data for the period 1993–2008 have been aggregated and raised according to annual catch estimates.

Effective (or standardised) effort was calculated by dividing catch by estimates of standardised CPUE. Standardised CPUE indices were obtained from GLM and generalised additive modelling (GAM) (Unwin et al. 2005) of data from New Zealand's domestic fishery. Effort for months without CPUE estimates was defined as "missing".

Sub-tropical Convergence Zone (STCZ) troll (TROLL 4). Catch (in weight) and effort data for US vessels have been provided by the US National Marine Fisheries Service (NMFS) by month and 5^0-square resolution for the period 1986–2008. Likewise, data for New Zealand's vessels have been provided at the same resolution. Where catch in number data are not available, catch in numbers have been determined from average weights estimated from size composition samples.

Driftnet (DN 3-4). Catch (in weight) and effort data (net length in km) by month and 5^0-square resolution have been provided by Japan (NRIFSF) for the Japanese driftnet fleet. Equivalent data for the Chinese Taipei fleet have been provided by Chinese Taipei (National Taiwan University). The Japanese and Chinese Taipei fleets use different effort units, and we have standardised Chinese Taipei driftnet effort to equivalent Japanese units by dividing Chinese Taipei catches by the monthly Japanese CPUE. Coverage of the entire South Pacific driftnet fishery represented by these data is unknown but is likely to be high during 1983–1991.

3.4.1 CPUE

There is a standardised CPUE index for each region and season for the 3 DWFN fleets. They are generally consistent (Figure 10), but there is some variation in the initial period of decline and the overall magnitude of the decline. A notable trend is the early decline for Japan, Korea and Chinese Taipei (i.e. distant-water longline fishing nations) in all regions. For these fleets, catch rates in the west (regions 1 and 3) were comparatively stable from the mid-1970s until the 1990s, while the eastern regions 2 and 4 show more of a decline. The Korean fleet in Region 2 experienced a peak of standardised CPUE in the mid-1990s, which may be an artefact of the standardisation process. Standardised CPUE data after 2000 are only available for the Chinese Taipei fisheries. With the single region model, all indices are assumed to apply to the same population, and the model balances the information in each index based on the assumed relative weights for each.

Non-standardised 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 from swordfish towards albacore. Fijian CPUE increased rapidly during the 1990s before becoming more variable. In Region 2, catch rates for the Samoan and American Samoan fleets have declined considerably since the early 1990s, although this pooled fishery represents a changing mixture of vessels with different catch rates. The Tongan fishery also shows a steep decline from the late 1980s until the present. Catch rates of the French Polynesian fleet increased from the early to late 1990s, and have declined steeply since then. In Region 3, the Australian longline CPUE during seasons 2 and 3 (September to March, or spring and summer) has increased since 2005, coincident with a change in targeting towards albacore. The New Zealand longline CPUE has declined since the late 1990s, and is associated with a switch in targeting towards swordfish. The "other" fisheries are a shifting mixture of fleets with differing catch rates, and are disregarded.

3.5 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. Data were collected from a number of sources, and can be summarised as follows.

Japanese, Korean, and Chinese Taipei longline (fisheries JP, KR, TW LL 1-4): The majority of 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 Japan (NRIFSF). In recent years, data have also been collected by OFP port samplers aboard Chinese Taipei longliners unloading in Fiji. Recent data provided by Chinese Taipei will be included in future once the model has been adapted to include data at a length resolution of 2 cm.

Domestic longline fleets (fisheries AU LL 1, NC LL 1, FJ LL 1, AS/WS LL 2, TO LL 2, PF LL 2, AU LL 3, NZ LL 3, and OTHER LL 1-4): Length-frequency data for these fleets were collected by port sampling programmes in most of the countries involved and by SPC or domestic observer programmes.

New Zealand domestic troll (TROLL 3): Data were collected from port sampling programmes conducted by the Ministry of Fisheries and, more recently, the New Zealand National Institute of Water and Atmospheric Research (NIWA).

STCZ troll (TROLL 4): Length-frequency data were 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 (DN 3-4): Data were provided by the NRIFSF for 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 12. No length samples were available 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 fishery's operation. For the long-standing Japanese, Korean and Chinese Taipei longline fisheries, length samples are available from the early 1960s onwards. However, length-frequency data collected in Pago Pago before 1971 were not included in this assessment (see also Hoyle *et al.* 2008b), leaving only samples from the Japanese longline fisheries from 1962 to 1970 (Figure 12).

For the northern regions (Regions 1 and 2), catches principally comprised large albacore (80–110 cm FL), while until recently, smaller fish comprised a high proportion of the catch from southern regions (Regions 3 and 4). For each of the main fisheries and particularly in the south, there was a general increase in the length of fish in catches from the 1960s to the 1990s (Figure 13). These trends are less pronounced than in the 2006 and previous assessments, since the region boundary was moved and fisheries were separated by season in the 2008 assessment.

3.6 Tagging data

Limited tagging data were available for incorporation into the MFCL analysis. Data consisted of tag releases and returns from OFP's albacore tagging programme conducted during the austral summers of 1990–1992 and from an earlier programme in the 1980s that involved members of the South Pacific Albacore Research Group (Figure 14). Tags were released using standard tuna tagging equipment and techniques by trained scientists and scientific observers. During 1990–1991, a limited amount of tagging was conducted from a chartered pole-and-line fishing vessel in New Zealand's coastal waters. In both years, the majority of tag releases were made by scientific observers onboard New Zealand and US troll vessels fishing in New Zealand's waters and in the central South Pacific STCZ region.

For the MFCL analysis, tag releases were 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 length-frequency data. In total, 9,691 releases were classified into 14 tag release groups (year and/or quarter). 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).

Tag releases principally comprised juvenile fish (aged 1–4 years); few fish larger than 80 cm (FL) were tagged (Figure 15). The length composition of fish from 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 longline fisheries in the southern regions (Regions 3 and 4), particularly fishery 18 (Figure 15). 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 tag recoveries occurred during the five years following the peak in releases (i.e. the early 1990s) (Figure 14).

Another albacore tagging programme was started by SPC in January 2009 (Williams *et al.* 2009). No tags have yet been returned, and no data from this tagging programme have yet been included in the model.

3.7 Biological parameters

Biological parameters included in the model are presented in Table 2. These were re-calculated for the 2008 assessment, based on analyses of biological data (Hoyle 2008). The calculations were based on data collected in the south Pacific, and based on relative reproductive potential rather than (as previously) the relative biomass of both sexes above the age of female maturity. The calculations used an approach also applied to bigeye (Hoyle & Nicol 2008) and yellowfin

(Hoyle et al 2009) tunas in the WCPO. The reproductive potential of each age class was assumed to be the product of the proportion of females at age, the proportion of females mature at age, the spawning frequency at age of mature females, and the fecundity at age per spawning of mature females. Overall, this results in a slight shift in the age of first maturity and a substantial reduction in the reproductive potential for older age classes relative to the values used in the 2006 assessment.

The length-weight relationship is estimated from available length-weight data (Hampton 2002). The von Bertalanffy growth parameters are provided as initial starting values in the model.

Variation in natural mortality (*M*) with age is assumed (Figure 11), at values estimated from sex ratio at length and maturity at length data (Hoyle 2008) using an approach previously applied to bigeye (Watters and Maunder 2001; Harley and Maunder 2003) and yellowfin (Maunder and Watters 2001) tunas in the EPO, and also applied to bigeye (Hoyle and Nicol 2008) and yellowfin tunas (Hoyle et al. 2009) in the WCPO. The increasing proportion of males in the catch with increasing size is assumed to be due to an increase in the natural mortality of females, associated with sexual maturity and the onset of reproduction.

4 Model description — structural assumptions, parameterisation and priors

As with any model, various structural assumptions have been made in the South Pacific albacore model. Such assumptions are always a trade-off to some extent between the need to keep the parameterisation as simple as possible (but make necessary assumptions for model processes), and the need to allow sufficient flexibility so that important characteristics of fisheries and fish populations are captured by 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 summarised in Table 3.

4.1 Observation models for the data

Three data components contribute to the log-likelihood function: total catch data, the length-frequency data and tagging data.

Observed total catch data are assumed to be unbiased and relatively precise, with the standard deviation (SD) of residuals on the log scale being 0.07.

4.1.1 Size frequency data

Conflicting information in the length frequency data and the CPUE time series have long been a feature of the south Pacific albacore stock assessment. For the present assessment, we made a number of changes to the way the length frequency data are modelled, and carried out several sensitivity analyses.

Probability distributions for length-frequency proportions are assumed to be approximated by robust normal distributions, with variance determined by the effective sample size and the observed length-frequency proportion. To obtain the effective sample size (ESS), the observed sample size (or 1000, whichever is less) is divided by the ESS divisor. The effective sample size is smaller than the observed (‘true’) sample size because length-frequency samples are neither truly random nor independent. Up to the 2006 assessment this divisor was 10, but for the 2008 assessment, due to results from a sensitivity analysis, the divisors were changed to 20, giving a maximum effective sample size of 50.

For this assessment, divisors for most longline fisheries in the southern regions 3, 4, and 6 were changed to 60, because the high variability suggested that either the samples were not very representative, or the selectivity of the fisheries was highly variable. To some extent it also reflects variability due to recruitment pulses. The divisor for the New Zealand longline fishery was left at 20 because the sizes of the samples were more consistent, and small enough to be useful for estimating growth rate. The divisors for the troll and driftnet fisheries were set to 10, reflecting their importance for estimating growth because of the relatively consistent length frequency samples (in recent years), and the monthly time step used for these fisheries.

The model was unable to provide a good fit to the length frequency data from the northern domestic longline fleets of New Caledonia and Australia, probably due to changes through time in targeting and fishing practises, and resulting changes in selectivity. Such different selectivities require separate fisheries, and until the data can be separated into different fisheries we chose to down-weight them with a divisor of 120, since retaining these data may bias the model results. For similar reasons, length frequency data for the ‘other’ combined fleets was down-weighted to be consistent, with a divisor of 120.

Smaller inconsistencies in the length frequency data were also observed in the LF data for the Fijian and French Polynesian fleets, and a divisor of 40 was applied.

These changes are discussed further later in this document. The effect of the overall change is examined in a sensitivity analysis.

An additional sensitivity analysis was carried out to examine the effect of the conflict between the CPUE and length frequency data. In the final phase of fitting the model, growth parameters and all selectivities were fixed at their estimated values, and length frequency data was down-weighted to a very low level by applying an ESS divisor of 500. This gave a maximum effective sample size of 2 per fishery per quarter and very high relative weight to the CPUE indices.

4.1.2 Tagging data

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

4.2 Tag reporting and mixing

Tag-reporting rates are estimated with relatively uninformative Bayesian priors, because 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, SD = 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 could also be immediate mortality due to tagging and tag shedding.

In previous assessments, tag-reporting rates were assumed to be equivalent across all four regions within each of the distant-water longline fishing nations. In this assessment tag reporting rates were allowed to vary between regions, reflecting a low probability that fish mix equally across all four regions, and evidence that estimated ‘return rates’ are considerably higher in regions closer to the site of release.

The single-region model structure does not accommodate anything other than full mixing across all four regions, and the use of reporting rates to account for different recovery rates by region is an overly simplistic way to model the processes occurring. However, given the low number of tags returned, this assumption does not significantly bias the model results. We assume that tagged albacore gradually mix with untagged populations and that this mixing process is complete after one year at liberty.

4.3 Recruitment

"Recruitment" in terms of the MFCL model is the appearance of age-class 1 fish in the population. Juvenile albacore tend to be caught mainly in the South Pacific's cooler temperate waters. In the single-region model currently used, new recruits are available to all fisheries mediated by the age-specific selectivity of individual fisheries.

From visual inspection of length-frequency data, the apparent seasonality of reproduction (Ramon and Bailey 1996) and the results of previous growth analyses (Labelle *et al.* 1993), it was further assumed that recruitment is an annual event that occurs in the summer months. 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 weak penalty was applied to deviation from the SRR so that it would have only a slight effect on 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 in order to have stable model behaviour. In the current assessment, the "steepness" coefficient (S) of the SRR was fixed at a moderate value of 0.75, 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 when the equilibrium spawning biomass is reduced to 20% of its unexploited level, equilibrium recruitment would be reduced to 75% of its unexploited level. Previous assessments have assumed steepness of 0.9, but the change was made this year to be consistent with the bigeye and yellowfin assessments. Sensitivity analyses were carried out to alternative steepness values of 0.55, 0.65, 0.85, and 0.95.

4.4 Age and growth

In previous assessments assumptions made concerning age and growth in the MFCL model were i) the lengths-at-age are normally distributed for each age class; ii) the mean lengths-at-age follow a von Bertalanffy growth curve; and iii) the standard deviations in length-at-age is a linear function of the mean length-at-age.

For this assessment, the second assumption above was modified. Previous analyses assuming a standard von Bertalanffy growth pattern indicated that there was substantial departure from the model for the smaller size classes, and that the model did not fit well to the cohorts of small fish observed in the troll fisheries. We therefore modelled growth by allowing the mean lengths of age-classes 2 to 5 to deviate from the von Bertalanffy growth curve. These deviations attract a small penalty to avoid over-fitting the size data. These changes are examined as sensitivity analyses, and included in the base case.

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.

4.5 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 minimising 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.

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 expected length-frequency distribution is more important, given the relative importance of length-frequency data in the total log-likelihood function. Previous assessments have highlighted conflicts between information in length-frequency data and CPUE data (Langley and Hampton 2005; Langley and Hampton 2006). Based on analyses of length-frequency data (Langley and Hoyle 2008; Bromhead *et al.* 2009), considerable work was undertaken to improve the way selectivity was modelled.

For the 2008 assessment, several changes were made to selectivity modelling. First, all longline fisheries were split into four by quarter. This change was made in order to accommodate strong seasonal variation in the length of fish caught (Langley and Hoyle 2008), which was noted in all regions.

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 more small fish. 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 fleet fishing practices. 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.

Selectivity functions for the troll and driftnet fisheries, which principally catch juvenile albacore, were not divided seasonally.

Selectivity for the troll fisheries was modified by estimating a bias in the first age class, under the assumption that this age class is not fully recruited to the model. This 'bias' is an offset that is added to the mean length of the first age class when calculating selectivity in these fisheries.

4.5.1 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). MFCL does not have the facility to vary selectivity through time within a fishery, since it is constrained to be constant. In the 2008 assessment we applied a sensitivity analysis using an alternative approach that splits 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, splits by fishery were offset from one another in time

For this assessment, residual patterns in the model fits to distant water longline length frequency data were examined for strong temporal changes. Where such changes were observed, fisheries were split in order to permit selectivity to change. These fishery splits were applied in 1977 to the Taiwanese fisheries in regions 1 and 2, the Japanese fisheries in regions 3 and 4, and the Korean fisheries in regions 2 and 4; and in 1983 to the Taiwanese fisheries in regions 2 and 4, and the Korean fisheries in regions 2 and 4.

4.6 Catchability

Catchability was assumed to be constant over time for all distant-water longline fisheries (Japanese, Korean and Chinese Taipei fleets), apart from the period before 1977, for reasons that will be discussed later. This assumption was based on the fact that CPUE for these fisheries was derived from the standardisation of data from vessels offloading albacore at Pago Pago canneries (Bigelow and Hoyle 2008). In the 2008 assessment, catchability was assumed to be constant for the troll fishery in Region 3 because the catch rate was based on a standardisation of New Zealand CPUE data (Unwin *et al.* 2005). However, this assumption was removed for the current assessment due to a re-examination of these data by New Zealand researchers, which suggested that catch rates are dominated by oceanography and availability, rather than by abundance (Adam Langley personal communication).

Catchability for all other fisheries was allowed to vary over time (akin to a random walk) using a structural time-series approach. Random walk steps were taken twice yearly (or annually in seasonal versions of the model), and deviations were constrained by a prior distribution of mean zero and a variance equivalent to a coefficient of variation (CV) of 0.7 on a log scale.

Seasonal variation in catchability — which was independently estimated for each fishery — was allowed in order 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 communications equipment, and/or higher vessel speeds — allow vessels to improve their ability to find and catch fish. The standardization of DWFN catch and effort data included a vessel effect, so this CPUE series takes into account changes in fishing power due to the introduction of new vessels. However, it does not include the effects of adding technology to existing vessels. As a sensitivity analysis relative to the base case model, we modelled this additional effort creep by increasing the catchability of all fisheries by 0.5% per year. This change would primarily affect the fisheries with standardised CPUE, and not those fisheries in which temporal catchability deviates are estimated.

4.7 Effort variability

Effort deviations are constrained by prior distributions having a mean of zero and a specified variance, and are used to model the random variation in effort (i.e. fishing mortality relation). In previous assessments, penalties were equivalent to an average CV of about 0.2 (log scale), with penalties on individual effort observations scaled by the square root of the effort.

In this assessment, time varying penalties on the effort deviations were implemented. For fisheries with standardized CPUE, penalties were adjusted to match the CV's estimated in the CPUE standardization (Bigelow and Hoyle 2009). This resulted in more weight being given to the indices from regions 1 and 2, and the Korean and Chinese Taipei indices. The effect of this change was investigated as a sensitivity analysis. A further sensitivity analysis applied a higher CV, reflecting the fact that variability in the relationship between CPUE and abundance is additional to estimation error in the CPUE.

4.8 Natural mortality

Mean natural mortality (*M*) was fixed at 0.4, with an alternative value of 0.3 trialled in sensitivity analyses and also used for estimating model structural uncertainty. *M* has been estimated in previous assessments, but is a difficult parameter for the model to estimate. Estimation was not attempted during this assessment.

Variation at age was as estimated from analysis of sex ratio at length data (Hoyle 2008). 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 and the subsequent loss of females 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. Alternative or complementary explanations for the observed patterns of sex ratio should be considered in future assessments.

The higher natural mortality likely to occur for young fish is not included in the model. Previous analyses applying higher natural mortality for young fish have shown little effect.

4.9 Initial population

The population was assumed to be at equilibrium in the first year of the model (1960). The initial age structure is determined as a function of estimated natural mortality and an initial fishing pressure, which is the average for the first three years of the assessment period.

4.10 Parameter estimation

The model's parameters were estimated by maximising the log-likelihood functions of the data plus the log of the probability density functions of the priors and smoothing penalties specified in the model. Maximisation was performed by an efficient optimisation, using exact derivatives with respect to 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 specific starting values that were consistent with available biological information.

4.11 Stock assessment interpretation methods

Several ancillary analyses were conducted in order to help interpret the stock assessment results for management purposes. The methods involved are summarised below and details can be found in Kleiber (2006). Note that in each case, confidence intervals for quantities of interest are available from the structural sensitivity analysis (described in section 4.12).

4.11.1 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 instead reflect recruitment variability.

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

4.11.2 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*), natural mortality (M), mean weight-at-age (w_a), mean recruitment $\bar{R}$, and the steepness parameter h. 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 parameter estimates of the model. The maximum yield with respect to *fmult* can easily be determined, and is equivalent to *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.

4.12 Alternative structural scenarios

A set of sensitivity analyses was run to examine the effects of alternative structural scenarios. We also used these analyses to estimate the size of the uncertainty associated with assumptions about the model structure. All scenarios were modelled both individually and in a structural uncertainty analysis, with all possible combinations of each set of factors:

- steepness parameter of 0.65, 0.75, 0.85, and 0.95;
- growth curve estimated, or fixed at the base case estimate;
- no effort creep, or 0.5% effort creep per year;
- mean natural mortality of 0.3 or 0.4;
- model start year of 1960 or 1971.
- LF data was either included as usual, or given minimal weight (maximum effective sample size of 2).

4.13 Summary of changes since last assessment

The main changes to the base-case model since the 2008 assessment were:

- The data were updated.
- A new time series of standardized CPUE for the distant water longline fisheries, using an improved method, was included.
- Time varying penalties based on the CPUE analysis were applied to the effort deviations.
- The standardised New Zealand troll CPUE was no longer assumed to be a reliable index of abundance.
- Data for the first two quarters of the first year and the last two quarters the final year were removed from the model, since the model year actually runs (and has always run) from July to June.
- Estimation of the growth curve was improved by estimating growth offsets for ages 2 to 5; aggregating the troll data on a monthly rather than quarterly time interval, so that growth cohorts could be tracked better; using new starting values for the estimation based on age 3 quarters in quarter 3; and delaying growth curve estimation until the model had estimated most other parameters.

- Selectivity was allowed to decline with age for the longline fisheries, except for those catching the largest fish.
- Selectivity 'bias' was introduced for the troll fisheries (an offset added to the mean length of the first age class when calculating selectivity in these fisheries), to allow for partial recruitment of the first age class.
- Effective sample sizes for length frequency data were reduced for most fisheries (i.e. reducing the relative importance of these data) because of inconsistencies.
- Most longline fisheries of the distant water fishing nations were split temporally to allow time-varying selectivities to be estimated.
- Tag reporting rates were estimated separately for distant water longline fisheries in separate regions;
- A lower value of steepness (0.75 rather than 0.9) was assumed.
- It was assumed that the steep decline in CPUE at the start of the time series was affected by changing catchability. A catchability trend was estimated for the earliest component of each of the DWFN fisheries.

Some of the above changes were recommended at a preparatory meeting in April 2009 at the SPC in Noumea, New Caledonia (Harley *et al.* 2009). A list of these recommendations and our responses is given in Table 4.

5 Results

In the current assessment, considerable effort was spent reviewing some of the model's underlying structural assumptions to better understand the impact of these assumptions on results. These sensitivity analyses include the changes described above in Section 4.13, which were included in the base-case model, as well as other changes described in the "Model Description" 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 and diagnostics of this model are presented in detail. Yield estimates and performance indicators are derived for the base-case assessment, and for the grid of models with alternative assumptions.

5.1 Structural changes

The primary aim of many of the changes referred to in Section 4.13, was to reduce 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 and Hampton 2005; Bromhead *et al.* 2009). As a result, the model has tended to estimate long-term trends in recruitment in order to reduce the data conflict.

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

Various model options for varying structural assumptions were examined with respect to trends in model estimates of adult biomass and annual recruitments (Figure 16–Figure 19) and described below. 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, log-likelihood values, and relative biomass depletion levels are reported in Table 5. The likelihood changes can often be used to compare how well different models fit the data, but only for models with the same data, and where the models give the same weights to the likelihood components.

Changes to data inputs and model phasing

5.1.1.1 Add new data

Fitting the model to the new data resulted in a significantly changed growth curve, with slower growth rate and larger variance of length at age. Largely as a result of the change in the growth curve, the estimated biomass increased considerably. The instability of the growth curve reflected a problem with local minima, which led to the following change in estimation sequence.

5.1.1.2 New growth estimation sequence

Changing the starting values for growth and the order of parameter estimation in the model again changed the growth curve significantly, and the biomass scaling also changed.

5.1.1.3 Revised GLM

Revising the GLM resulted in a steeper decline throughout the time series. In the CPUE series themselves, the problem of the large spikes in the Korean and Chinese Taipei CPUE series has been resolved, the new time series showing a more consistent pattern though time, with a general pattern of declining CPUE in recent years.

5.1.1.4 Change fisheries with non-decreasing selectivity

Imposing non-decreasing selectivity on the fisheries in which the largest fish were caught (longline fisheries in region 2 and season 4 from French Polynesia, Korea, and Chinese Taipei) had little effect on the total biomass, spawning biomass, or recruitment time series.

5.1.1.5 Remove NZ troll GLM

Removing the New Zealand troll GLM had no significant effect on the model.

Changes to model parameterisation

5.1.1.6 New growth options

The new growth model included growth offsets, reflecting more linear growth for age classes 2 to 5, higher growth rate (*K*), minor changes to *Lmin* and *Lmax*, and considerably more variation in length at age. These parameters were all fixed at this point, to avoid excessive variation between model runs. These new options resulted in a steeper decline overall, driven largely by the recruitment trend.

5.1.1.7 Midyear catch and effort

Changing the timing of the model to acknowledge that the model year begins in July did not significantly change the overall biomass trajectory. However, it resulted in higher initial (equilibrium) fishing mortality.

5.1.1.8 Reweight LF data

Reweighting the length frequency data to give less weight to samples from southern fisheries, and to fisheries with large changes in fishing behaviour through the time series, resulted in the model following the CPUE time series more closely. The early decline was steep, followed by a flat period from the mid-70s to the mid-80s. The decline resumed at a lower rate in the mid-1980's. The overall level of biomass decreased, reflecting reduced conflict between the CPUE and length frequency data. .

5.1.1.9 Time split

Adding time splits in longline fisheries (i.e. time-variant selectivities) further reduced the conflict between the CPUE and length frequency data, and resulted in a lower average estimated biomass level. The likelihood improved by 328 units, with 250 more parameters being estimated.

Change tag groups

Splitting the tag groups from different regions had very little effect on the estimates from the model, reflecting the limited influence of the tagging data on the model. However, it resulted in considerably better fit to the tagging data. The likelihood improved by 42 units, with 10 more parameters being estimated.

5.1.1.10 Use CPUE CV

Using the CV estimated from the CPUE time series resulted in more weight, on average, being given to the CPUE. The current biomass estimates were little changed but early biomass increased substantially. The likelihood is not comparable with the previous scenario.

5.1.1.11 First age selectivity bias

Selectivity bias for the first age class was estimated for the troll fishery, and the parameters *Lmin* and *K* and the growth offsets were estimated. L_{min} and *K* estimates were reduced, growth offsets were slightly smaller, and variance of length at age was little changed. In general, the model results changed little, apart from decreasing average biomass slightly. The overall likelihood was actually slightly worse than the previous scenario, reflecting the problem of local minima in growth estimates, and the fact that growth for the previous scenario was fixed at a better growth curve.

5.1.1.12 Monthly troll

The time interval of the troll fishery data was changed from quarterly to monthly to improve the resolution of cohorts growing through the fishery, and the growth parameters above were re-estimated. The most significant change was a reduction in the estimate of mean variation in length at age (gr_cv_slope). Average biomass increased substantially. It should be noted that the growth rates for most runs above were fixed at levels close to the level estimated in this and subsequent runs. The likelihood is not comparable with the previous scenario.

5.1.1.13 Estimate full growth curve

All the parameters of the growth curve were estimated, including those estimated above, the length at maximum age L_{max}, and the parameter defining the relationship between length and the variance of length at age. Growth rate *K* dropped 10%, L_{max} increased by about 1.5cm, but most important was a doubling in the rate of increase with length in the standard deviation of length at age. The average estimate of biomass reduced substantially. The fit to length frequency data from the troll fisheries was substantially better. The likelihood improved by 39 units over the previous scenario, with two extra parameters being estimated.

5.1.1.14 Steepness 0.75

Increasing the steepness of the stock recruitment relationship had minimal effect on any of the estimates of recruitment or biomass, or the likelihood. Only the MSY-related parameters changed.

Early biomass trend

The rapid decline in CPUE between 1965 and 1975 is seen in all the CPUE time series, and occurs during a period of high catch in region 2. However, at the estimated biomass level the reported catch is too low to cause the steep declines indicated by the model estimates through this period. Such steep declines in catch rate are often seen in the early development of a longline fishery (Polacheck 2006; Maunder *et al.* 2006; Gulland 1974). Several hypotheses could be advanced to explain this decline, mostly involving declines in catchability (Ahrens and Walters 2005). Individual fish vary in their vulnerability to capture, and removal of the more catchable individuals will lower the average catchability in the short to medium term. In addition, fish are capable of learning to avoid hooks, which results in lower catchability (Kieffer and Colgan 1992; Young and Hayes 2004). Finally, depletion of the more catchable individuals implies selection for low catchability, which may depress catch rates in the long term (Biro and Post 2008). We modelled the effect of short to medium term declines in catchability.

However, even if declining catchability is assumed, it is uncertain how much of the decline in CPUE was due to reduced catchability, and how much was due to reduced abundance due to fishing pressure. We therefore ran a model starting in 1971, after most of the decline had occurred, and estimated the depletion level at this time based on equilibrium assumptions.

5.1.1.15 Down-weight early CPUE data

CPUE data before 1971 were down-weighted by reducing the effort deviate penalty by a factor of 100. This resulted in substantially less decline in model biomass estimates between 1965 and 1975. Some decline remained and, since the catch was too low to drive the trend at the estimated biomass level, a recruitment trend was still required to drive the biomass decline. For abundances after the period of decline, and for the management parameters, down-weighting the CPUE data had no significant effects.

5.1.1.16 Early catchability trend (Base case)

Trends in catchability were estimated in the fisheries with standardized CPUE data, starting in 1960 and ending at the first time split, for the fisheries that were split for time-varying selectivity (in 1977 or 1983). For fisheries without time splits, catchability trends were estimated for the whole time series. As a result, the early biomass decline was replaced by a slight increase in biomass. This biomass increase was entirely driven by observed changes in the length frequency data. As above, for abundances after the period of decline, and for the management parameters, estimating an early catchability trend had no significant effects.

5.1.1.17 Start in 1971

Starting the model in 1971 resulted in remarkably similar management parameters, population levels for the last 10 years, and growth estimates. This indicates that the early data do not have much influence on the parameter estimates that largely determine the population dynamics. Differences before 1990 are probably driven by different selectivities being estimated for fisheries that have length frequency data before 1971. When length frequency data are down-weighted for the model starting in 1971, the overall biomass trends are very similar to those estimated in the model below.

Remaining conflict between LF and CPUE data

5.1.1.18 Down-weight LF fully

Down-weighting the length frequency data and fixing growth (in the last estimation phase) avoided the conflict between the length frequency data and the CPUE time series. The result was a steeper early decline in the biomass than was observed in the base case, and a lower biomass level overall. Recruitment variability was reduced to some extent, as expected given the removal of the recruitment signal in the length frequency data. The likelihood is not comparable with the previous model.

The "Early catchability trend" model encompassed the cumulative effects of the step-wise developments, excluding that for starting the model in 1971, and was selected as the base case model configuration to be used for the 2009 assessment.

5.1.2 Sensitivity to alternative assumptions

All models are based on assumptions. In many cases the 'right' assumption is not known, so it is important to measure the effects of choosing other plausible assumptions. We ran the base case model with several alternative assumptions, which we considered to be as plausible as the base case.

More detail of these changes is given above, in the 'Model description' section.

- Steepness of 0.65, 0.85, and 0.95, rather than 0.75
- Include effort creep of 0.5% per year.
- Mean adult natural mortality of 0.3 per year, rather than 0.4
- Start year of 1971 instead of 1960
- Down-weight length frequency data fully

5.1.2.1 Steepness = 0.65, 0.75, 0.85, 0.95

Varying the assumed steepness had, as expected, little effect on population dynamics but considerable impact on *MSY*-related parameters. Lower values of steepness resulted in more pessimistic stock status.

5.1.2.2 Effort creep 0.5%

Introducing 0.5% effort creep per year increased the rate of biomass decline as expected, since it implied that catch rates should be higher at the same biomass later in the time series. Adding effort creep had little effect on the likelihood value. B/B_{MSY} was the only management parameter significantly affected, with slightly more pessimistic outcomes.

5.1.2.3 Mean M = 0.3

Change the mean rate of adult natural mortality to 0.3 resulted in a better fit to the data by 5 units. Lower M implies a less productive stock, and stock assessment outcomes were somewhat less optimistic.

5.1.2.4 Start year 1971

Changing the start year to 1971 had little effect on the management parameters.

5.1.2.5 Down-weight LF data

Down-weighting the length frequency data generally resulted in a lower biomass level. F/F_{MSY} was the management parameter most affected, with a more pessimistic result.

5.2 Fit diagnostics

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

- The log total catch residuals by fishery (Figure 22) are relatively small, since large penalties constrain the estimated catch to be close to the observed catch. Where the deviates for key LL fisheries are close to zero for a period, this relates to missing effort data, so the catch can be fitted exactly. For the standardized fisheries the level of variation relates mostly to the precision of the CPUE estimates, with more precise estimates (and higher penalties) resulting in large catch deviates.

- The model predicts the number of tag recoveries from the population at each time interval (Figure 23). This is a function of the i) cumulative number of tag releases in the preceding period, ii) loss of tags from the population (due to natural mortality and previous catches), iii) level of fishing effort, iv) fishery-specific selectivity and catchability, and v) fishery-specific reporting rate for tag recoveries. Overall, the model predicts relatively low numbers of tag returns at each time interval, which is consistent with fishery observations. 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.

- Observed and predicted recoveries can also be compared with respect to the period at liberty of tagged fish (Figure 24). The model fit to tagging data for this version of the model is better than earlier versions that had higher biomass and lower fishing mortality, and better than the estimate from 2008, due to the improved treatment of tag reporting rates.

- 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 (Figure 25). This assumption may not be appropriate given the level of publicity associated with the initial release and/or recovery period. 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 reporting rates from individual fisheries. The model now uses tag reporting rates to account for the lack of full mixing between regions.

- Overall, the highest estimated reporting rates were from fisheries in region 3 and 4, with the maximum recorded by the New Zealand longline fishery in region 3 (50%). This largely reflects the fact that the tags were released in regions 3 and 4 and that mixing across the whole region is assumed, but this is not likely to be the case.

- For each fishery, the observed and predicted proportion of fish in each length class in the catch was compared for each sample (quarter). (These plots are too numerous to present here). Temporal trends remain in the residuals for some of the distant water longline fisheries. This is expected given the increasing lengths observed in the length-frequency data (Figure 12). There is also significant short-term variability among samples (Figure 26), suggesting non-random sampling of the catch or the population. Further analysis of the length frequency data is warranted in order to determine how to deal with these data appropriately.
- Strong residual trends remain in length-frequency data in a few domestic longline fisheries, including the New Caledonian and New Zealand longline fisheries. These trends may represent changes in selectivity, since they appear to coincide with switches in targeting. Given the selectivity trends, these data have been down-weighted so that they do not affect the model inappropriately.
- The model's overall consistency with observed effort data can be examined in plots of effort deviations against time for each fishery (Figure 27), and in 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 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.
- In general, the effort deviates are evenly distributed compared to the trends observed in the 2008 assessment. This indicates that the model is fitting the CPUE data reasonably well. Short term trends are apparent in residuals for all standardised fisheries, partly due to the remaining conflict between length-frequency data and CPUE data, and partly because CPUE trends from the different standardised fisheries are slightly different.
- The estimated exploitable biomass for each fishery can be compared with individual observations of catch and effort (scaled by catchability) from the fisheries (Figure 28). This figure illustrates the relatively high variation even in the standardised CPUE data, indicating the lack of precision associated with the catch and effort series — the model's principal index of stock abundance.

5.3 Model parameter estimates

5.3.1 Catchability

Annual catchability for standardised fisheries was permitted to vary for the first period of the model, but held constant after any split (Figure 29). Strong temporal declines in catchability are evident in these early periods. Many domestic longline fisheries reveal an initial increase in catchability during the development of the fishery, and a subsequent stabilisation of catchability. An exception to this trend was the decline in catchability evident in the Samoan and American Samoan longline fisheries (Figure 29). The New Zealand troll fishery shows two peaks of catchability in the late 1980's and late 1990's, which may relate to variation in availability. In recent years, catchability has declined in the troll fishery operating in Region 4. The steep increases in catchability seen in the previous assessment are not so evident, and trends are mixed.

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.

5.3.2 Selectivity

Selectivities for longline fisheries reveal some consistent seasonal patterns (Figure 30). However, the degree and pattern of variation among fleets and regions suggests that 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 (fisheries 1, 2 and 5) catch a higher proportion of older, adult albacore than most of those fisheries in the southern regions (fisheries 3, 4 and 6). The troll and driftnet 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.

Northern distant-water longline fleets are estimated to catch younger, smaller fish than do domestic fleets. This may be because, given the within-region spatial variation in fish size, they are fishing in locations where fish are smaller. In addition, their selectivity is assumed to be constant through time, and distant-water longline fleets have data from the 1960s and 1970s when smaller fish were caught.

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. Domestic fleets in northern regions also take smaller fish in season 2, with the largest fish generally taken in season 3. Since season 2 occurs before season 3, it may be useful to examine the timing of 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 for seasons 1 and 4.

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

5.3.3 Growth

The estimated growth curve is shown in Figure 31. Estimates are remarkably close to the Australian growth curve estimate, with the minor differences occurring for young fish less than about six years. The offsets estimated for this model suggest that growth of juvenile fish is more linear than the Australian growth curve, which assumes the von Bertalanffy model (Farley and Clear 2008).

The estimated variability of length-at-age increases with age, and is quite large for older age classes. It is unclear how much of this is true variability, and how much is the due to a) the model using variability to explain selectivity variation between fisheries, and b) size and/or growth variation between areas, not accounted for by the model. Biological research would help to determine the causes of this variation, and help improve the model, since variation of length at age can significantly affect model results.

5.4 Stock assessment results

Results for the base case model (section 5.1.1.16) are presented.

5.4.1 Recruitment

There is considerably less temporal variation in the average level of recruitment than was estimated in the 2008 and previous assessments (Figure 32). However, there is evidence of trends in recruitment driving trends in biomass, with recruitments initially increasing, and then declining.

The increasing estimated recruitments may reflect the model's attempt to fit the patterns in the length frequency data, since the model that down-weights those data exhibits no such increase. The decline in recruitment since the 1980s largely represents the model's attempt to fit a steeper decline in distant-water longline fisheries' CPUE than can be explained by the reported catch. The model with the length frequency data down-weighted estimated a lower level of biomass, and so was able to explain the CPUE trend with the reported catch, without estimating a trend in recruitment.

5.4.2 Biomass

Biomass is highly uncertain at the start of the 1960s, and depends entirely on the assumptions made about the early steep decline in catch rates (Figure 33). Scenarios that give weight to the early CPUE trends, and less consideration to an initial decline in catchability, estimate a steeply declining abundance trend up to the early 1970's. The base case assumes that CPUE before 1977 is independent of abundance, and the estimated biomass increases, driven by the signal in the length frequency data. The length frequency signal is not strong however, since it is easily overwhelmed by giving slightly more weight to the CPUE trend. When the length frequency data are down-weighted, a declining trend re-emerges. Given the high catch in region 2 during this period, a scenario with declining early biomass may be more realistic.

The biomass trend since 1980 is quite consistent among the principal models in the grid of 'equally likely' models, It is relatively stable until about 1990, and declining after this as total catches increase to twice their previous level.

We consider the lower biomass level estimated by models with down-weighted length frequency data to be at least as likely as the higher level estimated by models that fit to both datasets. As usual with this assessment, the overall level of biomass is lower when the conflict between the data series is reduced by giving the length frequency data less weight. When two information sources give conflicting information it can be misleading to try to fit to both, since this is the equivalent to assuming that both are true.

Biomass and spawning biomass levels are estimated to be close to equilibrium unfished levels until about 1990 (Figure 34), due to above average recruitment early in the time series. When length frequency data are down-weighted, initial biomass approaches B_0, and the following years are estimated to be below equilibrium unfished levels.

5.4.3 Fishing mortality

Fishing mortality (exploitation) rates for adult albacore are moderately low from the early 1970s to 2000, and show a large increase since that time, particularly for adult fish (Figure 35). Estimated exploitation rates have increased since 2000 in response to higher catches (Figure 6 and Figure 7) and the lower levels of adult biomass represented by the declining Chinese Taipei CPUE.

Fishing mortality rates for juvenile albacore are estimated to have gradually increased throughout the history of the fishery with a peak in 1989–1990 corresponding to the period of driftnet fishing. Fishing mortality in recent years is estimated to be on an increasing trend, largely due to the decline in estimated recruitment.

Estimated fishing mortalities for the fully recruited age classes have reached moderate levels since 2006, averaging about 0.2 for adults in the peak year 2005 (Figure 35), and averaging about 0.28 for fully recruited age classes (Figure 36). In the model with down-weighted length frequency data, fishing mortalities peak at about 0.4 for fully recruited age classes. By way of comparison, 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 (Langley *et al.* 2008).

5.4.4 Fishery impact

One way to examine fishing impact on the albacore stock is to compare 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 SRR). The impact can be expressed as a proportional reduction in biomass ($1-B_t/B_{t,F=0}$). It is calculated for different components of the stock: juveniles, spawning biomass, 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. Fishery impacts are consistent with 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 (2007) between about 50% and 75% (i.e. longline-vulnerable biomass has been reduced by between 25% and 50% due to the impact of fishing) (Table 9, Figure 37 and Figure 38). The current impact level on the component of the stock vulnerable to troll and driftnet fisheries is low (less than 5%). The difference is due to the age-specific selectivity of the longline fishery, which harvests fish in the oldest age classes. Only a relatively small component of the stock is available to the longline fishery, so increases in catch are likely to result in substantial increases in the impact on the longline exploitable biomass.

The impact on the longline exploitable biomass is higher in the longline fisheries operating in the northern regions (i.e. fisheries 1, 2 and 5) than the southern regions (i.e. fisheries 3, 4 and 6), due to a higher proportion of older fish in the catch in northern regions. Impacts also vary seasonally, with more effect on the seasons in which larger fish are taken (Figure 37 and Figure 38). The fishery's impact on the exploitable biomass in the troll and driftnet fisheries has been negligible throughout the fishery's history (Figure 37 to Figure 39).

Comparing the estimated impact of fishing on biomass (Figure 39) with the overall estimated biomass decline relative to initial biomass (Figure 40) demonstrates the degree to which the model is using recruitment to produce estimated biomass trends.

5.4.5 Yield analysis

Symbols used in the following discussion are defined in Table 8. Yield analyses conducted in this assessment incorporate the stock recruitment relationship (SRR) (Figure 41) into equilibrium biomass and yield computations. The assumed base case steepness coefficient of the SRR is 0.75, indicating a moderate relationship between stock and recruitment. Equilibrium yield and total biomass as functions of multiples of the 2005–2007 average fishing mortality-at-age (*Fmult)* are shown in Figure 42.

Results from the base case do not sit in the middle of the estimates from the uncertainty grid. In order to take the distribution of the uncertainty into account, all management parameters reported below use the median estimate from the grid.

Yield is maximised at *Fmult* = 3.5 for an *MSY* of 66,000 mt per year. This implies that the ratio $F_{2005-2007}/\tilde{F}_{MSY}$ is approximately 0.29. The equilibrium biomass at *MSY* is estimated at 550,000 mt, approximately 49% of the equilibrium unexploited biomass. Spawning biomass (reproductive potential) at MSY (SB_{MSY}) is estimated to be 24% of the unfished level (SB_{MSY}/SB_0).

5.4.6 Stock assessment conclusions

Various quantities of potential management interest associated with the yield analyses are provided in Table 9. Absolute quantities are provided in the top half of the table, while the bottom half 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 that compare a measure for a particular time period with the corresponding equilibrium measure; ii) ratios that compare two equilibrium measures (rows shaded grey); and iii) ratios that compare two measures pertaining to the same time period (row shaded black). Several commonly used reference points, such as $SB_{2007}/S\tilde{B}_{MSY}$, $B_{2005-2007}/\tilde{B}_{MSY}$ and $F_{2005-2007}/\tilde{F}_{MSY}$ 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 category ii ratios are considerably more robust than those in category i.

The ratios $B_{2005-2007}/B_{2005-2007,F=0}$ and $SB_{2007}/SB_{2007,F=0}$ can provide an indication of population depletion and fishing impact by the fisheries. Total biomass is estimated to be currently at 0.80 of its unfished level, and spawning biomass at 0.64 (i.e. spawning biomass reduced by 36% due to the impact of fishing). These represent a moderate level of depletion, above the equivalent equilibrium-based limit reference points ($\tilde{B}_{MSY}/\tilde{B}_0$ = 0.49 and SB_{MSY}/SB_0 = 0.24).

Other reference points useful in indicating the current stock status are $\tilde{B}_{F_{2005-2007}}/\tilde{B}_{MSY}$ (1.49) and $S\tilde{B}_{F_{2007}}/S\tilde{B}_{MSY}$ (2.36). Together with the yield-based reference point $\tilde{Y}_{F_{2005-2007}}/MSY$ (0.72), these suggest potential to expand long-term yields from the fishery at the current pattern of age-specific selectivity. However, higher fishing mortality would result in lower biomass levels and hence lower catch rates.

The ratios $F_{2005-2007}/\tilde{F}_{MSY}$ (0.29), $SB_{2007}/S\tilde{B}_{MSY}$ (2.44), and $B_{2005-2007}/\tilde{B}_{MSY}$ (1.53) do not indicate that overfishing of South Pacific albacore is occurring, nor do they indicate that the stock in an overfished state. The uncertainty distribution on the ratio $F_{2005-2007}/\tilde{F}_{MSY}$ indicates that the 90% probability distribution does not include values above 1 where overfishing occurs.

Time series of ratios of $F_t/\tilde{F}_{MSY}$, $B_t/\tilde{B}_{MSY}$, and $SB_t/S\tilde{B}_{MSY}$ (Figure 43 and Figure 44) indicate the fishery's trend 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 bringing the estimated biomass closer to B_{MSY}. B_{2007} is estimated to be moderately above B_{MSY}.

5.4.7 Alternative structural scenarios

The structural uncertainty scenarios may be used to compare equally plausible alternative scenarios.

Considerable uncertainty is evident with respect to all management parameters $SB_{2005-2007}$ / SB_{MSY}, $B_{2005-2007}$ / B_{MSY}, and $F_{2005-2007}$ / F_{MSY} (Figure 45); however, all estimates occur in the lower right quadrant of the Kobe plot. Uncertainties between spawning biomass and fishing mortality are strongly correlated.

We compared the effects of different components based on the results of the whole grid. Assumptions about steepness had the most effect on management parameters (Figure 46– Figure 48), giving more pessimistic outcomes for a steepness of 0.75 than for 0.95. More pessimistic outcomes also result (for at least one of the management ratios) when a lower estimate of natural mortality is used, length frequency data are given less weight, the model is started in 1971, or 0.5% more effort creep is included. In a few cases these results differ slightly from the tests of individual runs against the base case described earlier.

Box plots showing the distributions of management parameters and ratios are presented in Figure 49 and Figure 50.

6 Discussion and conclusions

The current stock assessment represents a significant reappraisal of the 2008 south Pacific albacore assessment (Hoyle *et al.* 2008a). It follows significant structural changes from the 2005 and 2006 assessments (Langley and Hampton 2005; Langley and Hampton 2006), which themselves represented a major reappraisal of previous assessments (Hampton 2002; Labelle and Hampton 2003).

Two major sources of uncertainty, identified in the 2008 assessment, have been considered and to some extent addressed in this assessment. The first issue was the conflict observed between CPUE trends in the longline fisheries and the information in the length frequency data. The second issue was uncertainty about how targeting changes may have affected recent CPUE for the Chinese Taipei longline fisheries.

Reappraisal of the two main datasets used in the model (CPUE and length frequency) was recommended given the observed conflict (Langley and Hampton 2005; Langley and Hampton 2006). The average size of fish caught progressively increased (with some variation) from the 1970s to the 1990's, while CPUE declined. If 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, because the model searches for parameter values that will accommodate both features at once. In these situations the model often inflates the overall biomass, and uses recruitment to make the biomass trend follow 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.

Cluster analyses, inclusion of additional data, and close examination of the effects of targeting have resulted in a more reliable CPUE series (Bigelow and Hoyle 2009) than the one used in the 2008 assessment (Bigelow and Hoyle 2008). Trends from all regions and fleets are relatively consistent, suggesting that in recent years the CPUE series should be considered a reliable indicator of the biomass trend. However, the steep early decline in the CPUE is unlikely to accurately reflect a similar decline in abundance, and was probably affected by changes in the catchability of the fish population.

Close examination of the length frequency data (Bromhead *et al.* 2009) suggests that the patterns of length frequency variation are broadly consistent with the changes in catches. However, some data are of poor quality, there may be sampling bias, and there is evidence of spatial and temporal variation (temporal changes in selectivity) that the model does not take into account. For these reasons, we have chosen to give more weight to the CPUE data than to the length frequency data as an indicator of abundance trend in this assessment. Correlations found between length trends, fleet movements and regional catch levels (Bromhead *et al.* 2009) are likely to result in better treatment of length data in future assessments.

Following on from the 2008 assessment, we have made further changes to the model configuration, in order to reduce the conflict between the data types. We have down-weighted some of the length frequency data and changed the model parameterisation (introducing time-varying selectivity). Model diagnostics and the likelihood value indicate that the model fits the data better than the previous configuration.

However, it is evident that conflict remains in the data. Problems are evident in the model diagnostics, such as large length-frequency residuals. Reducing the weight given to the length frequency data to very low levels, once growth and selectivity had been estimated, resulted in estimates with lower biomass and higher, but still moderate, fishing pressure. They also enabled the model to fit biomass trends without estimating long-term trends in recruitment.

Future work will take into account the results of recent analyses (Bromhead *et al.* 2009). These show spatial variation in fish size within regions, which may be taken into account by changing the spatial definitions of fisheries. Size trends that differ between regions are also consistent with differences in fishing mortality trends, suggesting that the model with separate sub-populations by region, not used for albacore since the 2005 assessment, should be revisited.

6.1 Biomass trends

Two major features are evident in CPUE data: the steep decline between 1960 and 1975, and the moderate decline after 1990.

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 as they become, on average, more wary of longlines. The model can accommodate this first decline by estimating initial equilibrium recruitment that is very high relative to mean recruitment. We have chosen to model this change as a decline in catchability, but the actual rate of catchability change before 1977 is unknown, so biomass before this time is also highly uncertain.

The second decline is driven by increasing catch and a decline in the standardised Chinese Taipei CPUE. Growth estimates and the CPUE series are more reliable in this assessment than in 2008, and the estimated decline is considered to be more credible. However, it remains somewhat steeper than can be accounted for by fishing pressure alone, even though total catch increases considerably over this period, so again the model uses recruitment to lower the exploitable biomass. In this case (if recruitment did not actually decline) the discrepancy may be occurring because the biomass estimates are elevated by the conflict between the data sources discussed above. At lower biomass levels, the increased catch since 1990 is sufficient to account for the observed CPUE decline.

6.2 Changes to the model

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

6.2.1 Changes to growth modelling

These changes resulted in the model fitting the length frequency data significantly better than in the 2008 assessment. In particular, the predicted length frequencies generally track the growth of cohorts through the troll fisheries very well. Distributions of length at age, to which stock status estimates are sensitive, appear reasonable for albacore tuna. The mean estimated lengths at age are remarkably close to estimates from otoliths (Farley and Clear 2008). These analyses were largely independent, which lends credibility to both results.

Lack of a reliable growth curve has been one of the most important sources of uncertainty in previous assessments. Future biological analyses are likely to further improve the growth curve. Areas for possible improvement include differences between sexes, spatial differences in growth rate, and better estimates of the variability of length at age.

6.2.2 Revised CPUE data

Potential changes in targeting were one of the two most important sources of uncertainty in the previous assessment. The revised CPUE data has largely resolved these questions, by using cluster analysis with the operational data to identify targeting. Future work should incorporate more operational data from the Chinese Taipei longline fishery. Some of these data have not previously been available for analysis, but potential collaborations with the Chinese Taipei Fisheries Agency should be explored.

6.2.3 Reconsideration of the length frequency data

Given the continuing uncertainty about the length frequency data and the way that conflicts with the CPUE data tend to result in higher biomass estimates, the reconsideration of the weight given to these data was appropriate. When information sources conflict, it is inconsistent to assume that both are right, and give both the same weight. Structural uncertainty analysis may be used to consider the possibilities that one or the other (but not both) is right. In this case we have more confidence in the CPUE data, so have down-weighted the LF data in several different ways.

6.3 Sensitivity analyses

Other sensitivity analyses were undertaken to explore the impact of assumptions about the SRR (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 (0.65 to 0.95), the ratio $F_{2005\text{-}2007} / F_{MSY}$ varied by a factor of 3. The albacore stock assessment is sensitive to assumptions about steepness (Hoyle 2008) because SB_{MSY} / SB_0 tends to be low, ranging from 14% to 30% depending on the steepness.

Effort creep, modelled at 0.5% per year, had a small effect on $F_{2005\text{-}2007} / F_{MSY}$, but more effect on the biomass ratios. The effort creep associated with introducing new vessels is already accounted for by the CPUE standardization, but additional effort creep is likely to be occurring. 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 (Langley 2004; Laurs *et al.* 1977; Chen *et al.* 2005), 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.

The uncertainty grid of models with alternative assumptions was carried out with all combinations of alternative steepness value (0.65, 0.75, 0.85, and 0.95), ± effort creep, natural mortality of 0.3 and 0.4, starting year of 1960 and 1971, and with and without the down-weighting of the length frequency data. Results showed a moderate range of variation in biomass, fishing mortality, and management parameters, indicating a moderate degree of structural uncertainty. This remains an under-estimate of the true uncertainty of the model, since parameter uncertainty is not included, and many assumptions are not included (e.g. regarding relatively constant q and selectivity, variation of natural mortality with age).

Limited tagging data were available for inclusion into the current assessment (a total of 138 recoveries). These data provide useful information about movement, harvest rates, 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 Samoan and American Samoan archipelago in recent years, and SPC carried out the first year of a two-year tagging programme in the New Zealand troll fishery in 2009.

Tag reporting rates estimated in this assessment are lower than those from most previous assessments, reflecting higher fishing mortality rates, and the freeing up of tag reporting rates among regions has permitted the model to fit the tag recapture data better. There are problems in estimating these reporting rates in a single-region model, given that the way the model deals with migration and mixing is somewhat inconsistent. However, the rate of decline in tag returns is relatively robust to these problems, and the model fits the data more successfully than did earlier configurations.

6.4 Management implications

Estimates of fishery impacts on biomass ($B_{current} \big/ B_{current,F=0}$) progressively increased between the 2003 assessment (3%), the 2005 (9%) and 2006 (10%) assessments, and the 2008 assessment (30%), as model configurations progressively changed. In this assessment the impact on biomass declines to 18%. Correspondingly, the *MSY* estimate from this assessment is above the 2008 estimate (97000 mt versus 64 000 mt, 181 000mt, 183 000 mt, and 300 000 mt in the last 4 assessments).

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, possibly associated with the northern and/or southern movements of fish during winter and/or summer. These peaks in seasonal catch rates tend to persist for a couple of months and to extend over a 10° latitudinal range (see Figure 5). 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 results of this assessment suggest that regional stock depletion has contributed to catch rate declines, but localised depletion may also have contributed. Observed declines in catch rates from significant domestic longline fisheries (e.g. Fiji, French Polynesia, and Samoa) — following periods of relatively high albacore catch (3,000–10,000 mt per year) — may indicate localised stock depletion (Langley 2004). Strong relationships may occur between catch rates and removals in the preceding 10 day period (Langley 2006). It is possible that movement rates into and out of EEZ’s are lower than peak catch levels, and there is some viscosity (perhaps residency) in the population.

It is also interesting to contrast the albacore fishery in the South Pacific with that in the North Pacific. The two fisheries are considered to consist of 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 mt and 120,000 mt since the 1950s, with approximately half of 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 are high (about 0.75), and recent catches are at about 60,000 mt.

These auxiliary observations lend support to the hypothesis that, with the current pattern of age-specific selectivity, a fishery at much above the current level – a level that has increased in recent years – is likely to reduce catch rates and economic returns. This increase has been paralleled by a reduction in CPUE, which together with increasing fuel prices has already affected the economics of the albacore fishery.

The current assessment estimates moderate levels of exploitation ($B_{2005-2007} \big/ B_{2005-2007,F=0}$ = 0.82, and $F_{2005-2007} \big/ \tilde{F}_{MSY}$ = 0.24). Nevertheless, given the estimated decline in recruitment, the current level of longline catches 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 20% and 50%, depending on the fishery, having increased sharply in recent years. The impact on the spawning biomass component of the stock is approximately 32%.

The model estimates that, in theory, increasing effort to F_{MSY} would yield somewhat more catch in the long term (equilibrium yield at current effort 63,000 mt; *MSY* 97,000 mt). However, higher yields at the current exploitation pattern of the fishery would require more fishing effort, resulting in lower adult biomass and lower longline catch rates. 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.

For the 2009 stock assessment we have focused on improving the reliability of the model's estimates of population dynamics. This is a pre-requisite for further analyses. Managers require advice that is both reliable and useful, and better estimates of population dynamics will in future provide the foundation for more relevant modelling, such as evaluating management strategies against performance indicators, including those based on something other than MSY.

6.5 Conclusions and recommendations

Stock status

- Levels of stock size and *MSY* appear more realistic than in the 2008 assessment, because many sources of potential bias have been removed.
- However, uncertainty remains over a moderate range of biomass and fishing mortality levels.
- Models that down-weight the length frequency data (in order to rely on the index of abundance from the CPUE data), tend to give lower biomass relative to B_{MSY}, and higher fishing mortality relative to F_{MSY}, throughout the time series.
- There is considerable uncertainty about the early biomass trend, but this has negligible effect on the management parameters (Table 5).
- Estimates of $F_{2005\text{-}2007}/F_{MSY}$ (from 0.1 to 0.5) and $SB_{2005\text{-}2007}$ / SB_{MSY} (from 1.7 to 4.9) are quite variable between model configurations, but the variation does not include overfishing, above F_{MSY}, or an overfished state below SB_{MSY}.

- Most of the variation in management parameters is attributable to steepness – something we have no information about. This variation makes management advice (based on MSY) relatively uninformative. Alternative metrics such as the expected CPUE, relative to a target CPUE, may be both more relevant and more precise.
- There is no indication that current levels of catch are not sustainable in terms of recruitment overfishing, particularly given the age selectivity of the fisheries. However, current levels of fishing pressure appear to be affecting longline catch rates.

Recommended model developments

- Thoroughly investigate the length frequency data in order to resolve the data conflicts which continue to affect the model, and may be biasing abundance estimates.
- Through collaboration with scientists (and industry) from distant water fishing nations, develop better understanding of changes in fishing practices over time, which may affect estimates of catchability and selectivity.
- Investigate alternative reference points that may be more relevant and more precise.
- An integrated assessment of North and South Pacific albacore would be beneficial. 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.
- Adjust the spatial definitions of fisheries to take spatial size variation within regions into account.
- Investigate length-based selectivity, which may help to improve the estimated distribution of length-at-age.
- Develop approaches in MFCL to change selectivity through time, possibly with a covariate.
- Models with separate regional sub-populations should be explored.

Related research

- Carry out biological research to provide better information for the growth curve, particularly growth differences between sexes, variation in length at age for the oldest fish, and the nature of regional variation in growth.
- Carry out biological research to provide sex-specific age data to examine the hypothesis of greater female natural mortality.
- Carry out biological sampling to obtain a representative age distribution of longline catch.
- Better information about appropriate model structure is needed, and growth and movement information would support this development. Electronic tagging work to determine fish movement patterns is desirable. Independent estimates of tag-return rates, tag loss, and tagging-related mortality would increase the usefulness of conventional tagging data in estimating fishing mortality rates.

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8 Tables

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

Fishery	Fishery label	Region	Method	Flag	Catch	Effort
1	JP LL 1	1	Longline	Japan	Number	Hooks (100s)
2	KR LL 1	1	Longline	Korea	Number	Hooks (100s)
3	TW 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 LL 2	2	Longline	Japan	Number	Hooks (100s)
9	KR LL 2	2	Longline	Korea	Number	Hooks (100s)
10	TW 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 LL 3	3	Longline	Japan	Number	Hooks (100s)
16	KR LL 3	3	Longline	Korea	Number	Hooks (100s)
17	TW 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 LL 4	4	Longline	Japan	Number	Hooks (100s)
22	KR LL 4	4	Longline	Korea	Number	Hooks (100s)
23	TW 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-weight relationship	a = 6.9587e-06, b =3.2351	Fixed
Growth (von Bertalanffy)	$L_{t=1}$ = 40.437 cm, *k* = 0. 0.347, Linf = 101.7 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 sizes (ESS) for longline fisheries in the north (regions 1 and 2) and south (3 and 4) are assumed to be 1/20th and 1/60th actual sample size respectively, with the following exceptions. ESS for Australian, New Caledonian and 'Other' longlines fisheries was assumed to be 1/120th actual; and ESS for Fijian and French Polynesian longline fisheries was assumed to be 1/40th actual. ESS for Troll and Driftnet fisheries is assumed to be 1/10th actual. In each case the maximum actual ESS was 1000 / the ESS divisor.
Observation model for tagging data	Tag numbers in a stratum have Poisson probability distribution.
Tag reporting	Longline reporting rates within each fishery 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 January of each year. Recruitment is weakly related to spawning biomass with a one-year lag via a Beverton-Holt SRR (steepness = 0.75).
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 within each fishery, though some fisheries are split temporally. Coefficients for the last 2 age-classes are constrained to be equal.
Catchability	Seasonal variation for troll and driftnet fisheries. For fisheries with effort based on standardized CPUE (DWFN fisheries), catchability is estimated separately for each season. All non-DWFN fisheries have structural time-series variation, with random steps (catchability deviations) taken every twelve 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. For DWFN fisheries the CPUE SD is applied. For other fisheries the SD is 0.22.
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 April 2009 preparatory meeting, and whether they were carried out for this stock assessment.

	Option	Investigated?	Base case?	Sensitivity analysis?
1	Revise spatial stratification – additional strata in the east (for new fishery definitions)	Other options preferred given time constraints	No	No
2	Improved CPUE series – for the main LL fisheries. Collaboration with TWN and NZ researchers (free up catchability for NZ troll fishery)	Yes, SA-WP-5	Yes	Yes
3	Address decadal changes in the mean size of fish in the catch and other spatial-temporal patterns in size composition data. Many options to address this depending on the outcomes of the data analyses.	Yes, SA-IP-5.		
3a	Most likely increase the number of longitudinal spatial strata in regions 2 and 4 in particular.	No	No	No
3b	Variable growth in each region (maybe more data needed) and model each region separately	Modelled separate regions, growth rates	No	Yes
3c	Further development of the time-split	Yes	Yes	Yes
4	Growth-related issues. Considering regional growth and alternative fixed growth curves.	Many approaches to improving growth curve	Yes	Yes
5	Other length-related issues: cleaning up the size data to make sure that it is weighted properly (e.g. samples were weighted to the catch). Apply length-specific selectivity.	Down-weighted some LF data; length selectivity;	Yes; No.	Yes; Yes
6	Monthly time step for surface fisheries	Yes	Yes	Yes
7	Catch conditioned	No		
8	2cm length bins	No		
9	Reconsider tagging data	Changed tag groups	Yes	Yes

Table 5: **For each progressive change in model configuration, likelihood, number of parameters, and relationship between estimated current biomass and unfished biomass. Row 16 is in bold, because it was selected as the base case. Results of the sensitivity analyses are presented below.**

Model configuration	**log likelihood**	**gradient**	**# pars**	SB_{2007} / SB_{MSY}	$F_{2005\text{-}2007}$ / F_{MSY}	***K***	***Lmin***	***L*max**
0.Last year	-344,872	0.0000	5637	2.74	0.439	0.383	34.3	101.1
1.New data	-421,201	0.0010	5381	3.68	0.083	0.277	39.9	102.7
2.New growth sequence	-372,485	0.0008	5381	3.38	0.153	0.355	34.3	101.4
3.Revised GLM	-411,520	0.0009	5365	3.30	0.126	0.369	33.0	100.9
4.Non-dec sel change fisheries	-411,515	0.0008	5365	3.31	0.117	0.320	36.0	102.2
5.Remove NZ troll GLM	-411,383	0.0008	5404	3.32	0.107	0.314	36.3	102.3
6.New growth options	-411,482	0.0009	5400	3.31	0.103	0.347	40.4	101.7
7.Mid year CE	-410,870	0.0010	5335	3.19	0.120	0.347	40.4	101.7
8.Rewt LF data	-331,507	0.0008	5335	3.15	0.139	0.347	40.4	101.7
8b.Tag groups	-331,549	0.0053	5345	3.16	0.138	0.347	40.4	101.7
9.Time split	-331,877	0.0009	5593	3.20	0.159	0.347	40.4	101.7
10.Use CPUE CV	-331,617	0.0068	5593	3.03	0.150	0.347	40.4	101.7
11.First age sel bias	-331,584	0.0096	5601	2.98	0.163	0.358	37.0	101.7
12.Monthly troll	-348,355	0.0054	5789	3.18	0.107	0.347	37.4	101.7
13.Est full growth curve	-348,383	0.0008	5791	3.04	0.144	0.323	38.5	102.9
14.Steepness 0.75	-348,384	0.0049	5791	2.12	0.242	0.323	38.5	102.9
15.Downwt early CPUE	-348,787	0.0009	5791	2.19	0.242	0.317	38.7	103.1
16.Early catchability trend	**-349,006**	**0.0010**	**6803**	**2.28**	**0.253**	**0.312**	**38.8**	**103.3**
17.Downweight LF fully	-133,506	0.0075	6206	2.04	0.353	0.312	38.8	103.3
18.Start 1971	-326,736	0.0164	5290	2.47	0.246	0.302	40.9	103.4

Table 6: Details of objective function components.

Objective function component	
Number of parameters	5791
Total catch log-likelihood	107.6
Length frequency log-likelihood	-351645
Tag log-likelihood	445.1
Effort dev penalty	1726.2
Penalties	2076.8
Total function value	- 349,987.3
Maximum gradient at termination	0.0010

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

			Season					
Method	**Region**	**Flag**	**1**	**2**	**3**	**4**	**ALL**	
L	1	AU	-252	-590	-249	-28		-1,119
		FJ	-2,197	-3,117	-3,212	-3,140		-11,666
		JP	-5,866	-5,436	-8,413	-5,997		-25,711
		KR	-3,725	-4,598	-5,033	-3,502		-16,858
		NC	-3,083	-3,292	-3,343	-3,187		-12,905
		OT	-2,097	-2,409	-2,122	-1,515		-8,142
		TW	-6,544	-5,181	-5,541	-5,296		-22,562
	2	AS,WS	-2,636	-2,854	-2,461	-2,491		-10,441
		JP	-5,312	-7,687	-6,335	-7,238		-26,572
		KR	-6,463	-5,054	-6,061	-6,272		-23,850
		OT	-2,409	-2,256	-2,324	-1,459		-8,448
		PF	-3,561	-3,065	-3,120	-3,428		-13,174
		TO	-3,258	-3,673	-3,510	-3,237		-13,678
		TW	-7,083	-4,712	-5,157	-6,914		-23,865
	3	AU	-575	-1,144	-1,161	-746		-3,626
		JP	-1,624	-5,856	-5,692	-1,191		-14,363
		KR	-294	-2,182	-1,992	-698		-5,165
		NZ	-2,703	-3,183	-2,078	-1,693		-9,657
		OT	-352	-633	-1,375	-609		-2,968
		TW	-255	-1,864	-3,494	-221		-5,834
	4	JP	-350	-2,127	-1,793	-800		-5,071
		KR	-1,352	-3,318	-2,585	-676		-7,932
		OT	-963	-1,505	-1,719	-831		-5,017
		TW	-2,206	-5,304	-5,357	-771		-13,638
	5	JP	-449	-2,798	-6,056	-2,180		-11,483
	6	JP	-660	-2,301	-2,970	-2,304		-8,235
T	3	ALL					-21,044	-21,044
	4	ALL					-16,567	-16,567
D	3	ALL					-1,368	-1,368
	4	ALL					-686	-686
Grand Total			-66,267	-86,135	-93,153	-66,425	-39,665	-351,645

Table 8: Descriptions of symbols used in the yield analysis.

Symbol	Description
$F_{2005-2007}$	Average fishing mortality-at-age for 2005–2007
F_{MSY}	Fishing mortality-at-age producing the maximum sustainable yield (*MSY*)
$\tilde{Y}_{F_{2005-2007}}$	Equilibrium yield at $F_{2005-2007}$
$\tilde{Y}_{F_{MSY}}$ (or *MSY*)	Equilibrium yield at F_{MSY}, or maximum sustainable yield
$\tilde{B}_0$	Equilibrium unexploited total biomass
$\tilde{B}_{F_{2005-2007}}$	Equilibrium total biomass at $F_{2005-2007}$
$\tilde{B}_{MSY}$	Equilibrium total biomass at MSY
$S\tilde{B}_0$	Equilibrium unexploited adult biomass
$S\tilde{B}_{F_{2007}}$	Equilibrium adult biomass at $F_{2005-2007}$
$S\tilde{B}_{MSY}$	Equilibrium adult biomass at MSY
$B_{2005-2007}$	Average current (2005–2007) total biomass
SB_{2007}	Average current (2005–2007) adult biomass
$B_{2005-2007,F=0}$	Average current (2005–2007) total biomass in the absence of fishing.

Table 9: Estimates and 90% distributions of management quantities from the uncertainty analysis. For comparison, results are given from the base case, and the sensitivity analysis with minimal weight given to the length frequency data. 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**	Median	5%	95%
$C_{2005\text{-}2007}$	mt	65,801	64,605	66,694
$YF_{2005\text{-}2007}$	mt / year	235,820	212,480	260,640
MSY	mt / year	81,580	58,683	121,855
$YF_{2005\text{-}2007}$ / MSY		0.72	0.52	0.92
$C_{2005\text{-}2007}$ / MSY		0.80	0.54	1.13
F_{MSY}		0.16	0.12	0.20
$F_{2005\text{-}2007}$ / F_{MSY}		0.29	0.11	0.60
B_0	mt	1,098,500	868,050	1,408,900
B_{MSY}	mt	553,200	393,660	734,600
B_{MSY} / B_0		0.49	0.45	0.54
$B_{2005\text{-}2007}$	mt	863,665	619,316	1,106,590
$BF_{2005\text{-}2007}$	mt	836,300	553,100	1,171,900
$B_{2005\text{-}2007}F_0$	mt	1,084,933	875,645	1,300,042
SB_0		406,600	356,140	510,450
SB_{MSY}		101,700	56,841	143,645
SB_{MSY} / SB_0		0.24	0.14	0.32
SB_{2007}		236,793	191,966	317,931
SBF_{2007}		235,250	177,010	335,705
$SB_{2007}F_0$		390,193	355,893	463,218
$B_{2005\text{-}2007}$ / B_0		0.76	0.69	0.83
$BF_{2005\text{-}2007}$ / B_0		0.74	0.62	0.83
$B_{2005\text{-}2007}$ / B_{MSY}		1.53	1.41	1.69
$BF_{2005\text{-}2007}$ / B_{MSY}		1.49	1.27	1.68
$B_{2005\text{-}2007}$ / $B_{2005\text{-}2007}F_0$		0.80	0.71	0.85
SB_{2007} / SB_0		0.60	0.52	0.66
SBF_{2007} / SB_0		0.59	0.48	0.68
SB_{2007} / SB_{MSY}		2.44	1.69	4.46
SBF_{2007} / SB_{MSY}		2.36	1.49	4.56
SB_{2007} / $SB_{2007}F_0$		0.64	0.53	0.71

Table 10: Management parameters from the base case and

Management quantity	**Base case**	**Low LF**
$C_{2005\text{-}2007}$	66,869	63,209
$YF_{2005\text{-}2007}$	64,490	58,980
MSY	97,610	74,920
$YF_{2005\text{-}2007} / MSY$	0.66	0.79
$C_{2005\text{-}2007} / MSY$	0.69	0.84
F_{MSY}	0.14	0.14
$F_{2005\text{-}2007} / F_{MSY}$	0.25	0.35
B_0	1,309,000	997,100
B_{MSY}	692,100	531,000
B_{MSY} / B_0	0.53	0.53
$B_{2005\text{-}2007}$	965,860	764,077
$BF_{2005\text{-}2007}$	1,041,000	739,700
$B_{2005\text{-}2007}F_0$	1,159,433	953,567
SB_0	460,400	350,900
SB_{MSY}	120,000	91,350
SB_{MSY} / SB_0	0.26	0.26
SB_{2007}	273,557	186,530
SBF_{2007}	292,500	190,300
$SB_{2007}F_0$	402,873	313,643
$B_{2005\text{-}2007} / B_0$	0.74	0.77
$BF_{2005\text{-}2007} / B_0$	0.80	0.74
$B_{2005\text{-}2007} / B_{MSY}$	1.40	1.44
$BF_{2005\text{-}2007} / B_{MSY}$	1.50	1.39
$B_{2005\text{-}2007} / B_{2005\text{-}2007}F_0$	0.83	0.80
SB_{2007} / SB_0	0.59	0.53
SBF_{2007} / SB_0	0.64	0.54
SB_{2007} / SB_{MSY}	2.28	2.04
SBF_{2007} / SB_{MSY}	2.44	2.08
$SB_{2007} / SB_{2007}F_0$	0.68	0.59

Table 11a: Sensitivity analyses

Management quantity	h = 0.65	h = 0.85	h = 0.95	Actual Early CPUE
$C_{2005\text{-}2007}$	66,423	66,501	66,446	66,498
$YF_{2005\text{-}2007}$	59,600	61,950	62,940	63,410
MSY	84,100	112,300	129,300	104,000
$YF_{2005\text{-}2007} / MSY$	0.71	0.55	0.49	0.61
$C_{2005\text{-}2007} / MSY$	0.79	0.59	0.51	0.64
F_{MSY}	0.12	0.16	0.20	0.14
$F_{2005\text{-}2007} / F_{MSY}$	0.31	0.16	0.10	0.22
B_0	1,317,000	1,330,000	1,322,000	1,410,000
B_{MSY}	705,300	694,500	656,200	749,500
B_{MSY} / B_0	0.54	0.52	0.50	0.53
$B_{2005\text{-}2007}$	1,051,167	1,087,767	1,078,233	1,107,100
$BF_{2005\text{-}2007}$	1,032,000	1,105,000	1,113,000	1,152,000
$B_{2005\text{-}2007}F_0$	1,244,667	1,281,267	1,271,633	1,300,533
SB_0	456,600	461,000	458,200	488,700
SB_{MSY}	138,500	97,140	65,530	127,000
SB_{MSY} / SB_0	0.30	0.21	0.14	0.26
SB_{2007}	296,417	308,283	304,803	315,030
SBF_{2007}	289,700	312,400	314,200	327,100
$SB_{2007}F_0$	426,427	438,340	434,777	444,847
$B_{2005\text{-}2007} / B_0$	0.80	0.82	0.82	0.79
$BF_{2005\text{-}2007} / B_0$	0.78	0.83	0.84	0.82
$B_{2005\text{-}2007} / B_{MSY}$	1.49	1.57	1.64	1.48
$BF_{2005\text{-}2007} / B_{MSY}$	1.46	1.59	1.70	1.54
$B_{2005\text{-}2007} / B_{2005\text{-}2007}F_0$	0.84	0.85	0.85	0.85
SB_{2007} / SB_0	0.65	0.67	0.67	0.64
SBF_{2007} / SB_0	0.63	0.68	0.69	0.67
SB_{2007} / SB_{MSY}	2.14	3.17	4.65	2.48
SBF_{2007} / SB_{MSY}	2.09	3.22	4.79	2.58
$SB_{2007} / SB_{2007}F_0$	0.70	0.70	0.70	0.71
Objective function	350,002	350,003	350,002	349,987
Number of parameters	5,815	5,815	5,815	5,791

Table 10: Management parameters from the base case and

Management quantity	Base case	Low LF
$C_{2005\text{-}2007}$	66,869	63,209
$YF_{2005\text{-}2007}$	64,490	58,980
MSY	97,610	74,920
$YF_{2005\text{-}2007} / MSY$	0.66	0.79
$C_{2005\text{-}2007} / MSY$	0.69	0.84
F_{MSY}	0.14	0.14
$F_{2005\text{-}2007} / F_{MSY}$	0.25	0.35
B_0	1,309,000	997,100
B_{MSY}	692,100	531,000
B_{MSY} / B_0	0.53	0.53
$B_{2005\text{-}2007}$	965,860	764,077
$BF_{2005\text{-}2007}$	1,041,000	739,700
$B_{2005\text{-}2007}F_0$	1,159,433	953,567
SB_0	460,400	350,900
SB_{MSY}	120,000	91,350
SB_{MSY} / SB_0	0.26	0.26
SB_{2007}	273,557	186,530
SBF_{2007}	292,500	190,300
$SB_{2007}F_0$	402,873	313,643
$B_{2005\text{-}2007} / B_0$	0.74	0.77
$BF_{2005\text{-}2007} / B_0$	0.80	0.74
$B_{2005\text{-}2007} / B_{MSY}$	1.40	1.44
$BF_{2005\text{-}2007} / B_{MSY}$	1.50	1.39
$B_{2005\text{-}2007} / B_{2005\text{-}2007}F_0$	0.83	0.80
SB_{2007} / SB_0	0.59	0.53
SBF_{2007} / SB_0	0.64	0.54
SB_{2007} / SB_{MSY}	2.28	2.04
SBF_{2007} / SB_{MSY}	2.44	2.08
$SB_{2007} / SB_{2007}F_0$	0.68	0.59

Table 11b: Sensitivity analyses

Management quantity	Creep	M=0.3	Start 1971	LF data wt
$C_{2005\text{-}2007}$	66,479	66,506	66,473	64,696
$YF_{2005\text{-}2007}$	64,000	54,720	58,600	58,910
MSY	104,000	67,780	85,820	83,940
$YF_{2005\text{-}2007} / MSY$	0.62	0.81	0.68	0.70
$C_{2005\text{-}2007} / MSY$	0.64	0.98	0.77	0.77
F_{MSY}	0.14	0.14	0.14	0.14
$F_{2005\text{-}2007} / F_{MSY}$	0.22	0.39	0.26	0.28
B_0	1,410,000	975,900	1,162,000	1,132,000
B_{MSY}	749,300	470,800	618,800	604,100
B_{MSY} / B_0	0.53	0.48	0.53	0.53
$B_{2005\text{-}2007}$	1,087,867	743,627	944,013	928,737
$BF_{2005\text{-}2007}$	1,149,000	672,600	917,200	884,500
$B_{2005\text{-}2007}F_0$	1,281,267	1,000,257	1,138,133	1,119,733
SB_0	488,700	417,000	403,100	392,500
SB_{MSY}	127,000	117,800	105,100	101,900
SB_{MSY} / SB_0	0.26	0.28	0.26	0.26
SB_{2007}	310,293	254,807	262,177	240,517
SBF_{2007}	325,400	230,300	250,600	238,000
$SB_{2007}F_0$	440,080	419,787	393,503	369,567
$B_{2005\text{-}2007} / B_0$	0.77	0.76	0.81	0.82
$BF_{2005\text{-}2007} / B_0$	0.81	0.69	0.79	0.78
$B_{2005\text{-}2007} / B_{MSY}$	1.45	1.58	1.53	1.54
$BF_{2005\text{-}2007} / B_{MSY}$	1.53	1.43	1.48	1.46
$B_{2005\text{-}2007} / B_{2005\text{-}2007}F_0$	0.85	0.74	0.83	0.83
SB_{2007} / SB_0	0.63	0.61	0.65	0.61
SBF_{2007} / SB_0	0.67	0.55	0.62	0.61
SB_{2007} / SB_{MSY}	2.44	2.16	2.49	2.36
SBF_{2007} / SB_{MSY}	2.56	1.96	2.38	2.34
$SB_{2007} / SB_{2007}F_0$	0.71	0.61	0.67	0.65
Objective function	350,003	350,007	326,741	134,408
Number of parameters	5,815	5,815	5,314	5,218

9 Figures

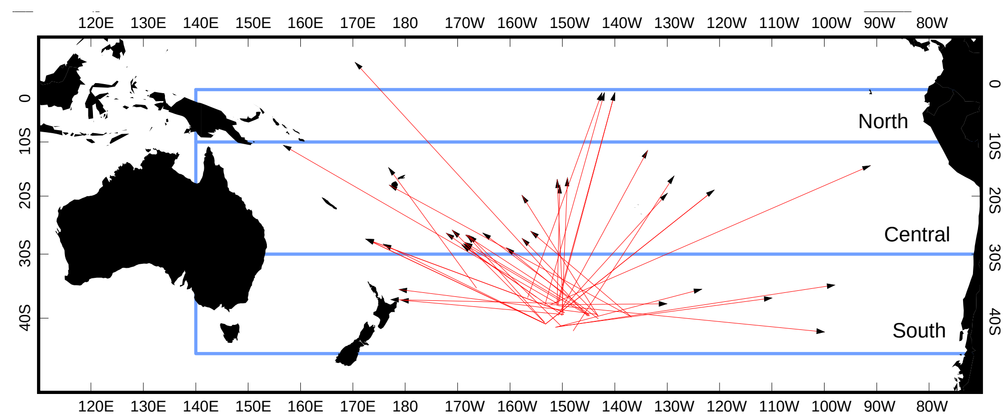


Figure 2: Movements of tagged South Pacific albacore (from Labelle and Hampton 2003).

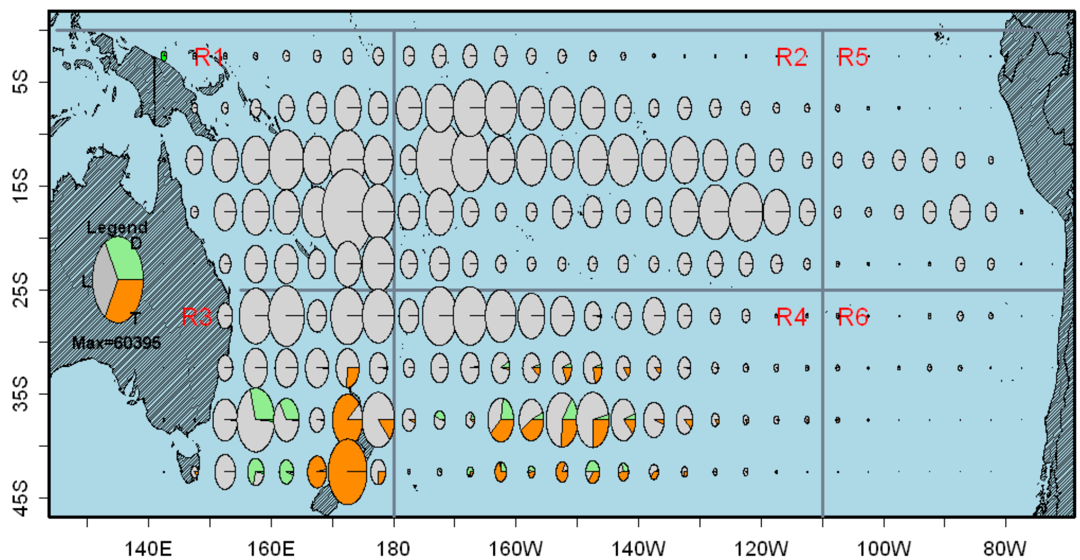


Figure 3: Total catch from 1960 to 2008 by 5^0 squares of latitude and longitude by fishing gear: longline (L), driftnet (G), and troll (T). The area of the pie chart is proportional to the total catch. The boundary of the stock assessment area is delineated by the black line and regional boundaries are delineated by grey lines.

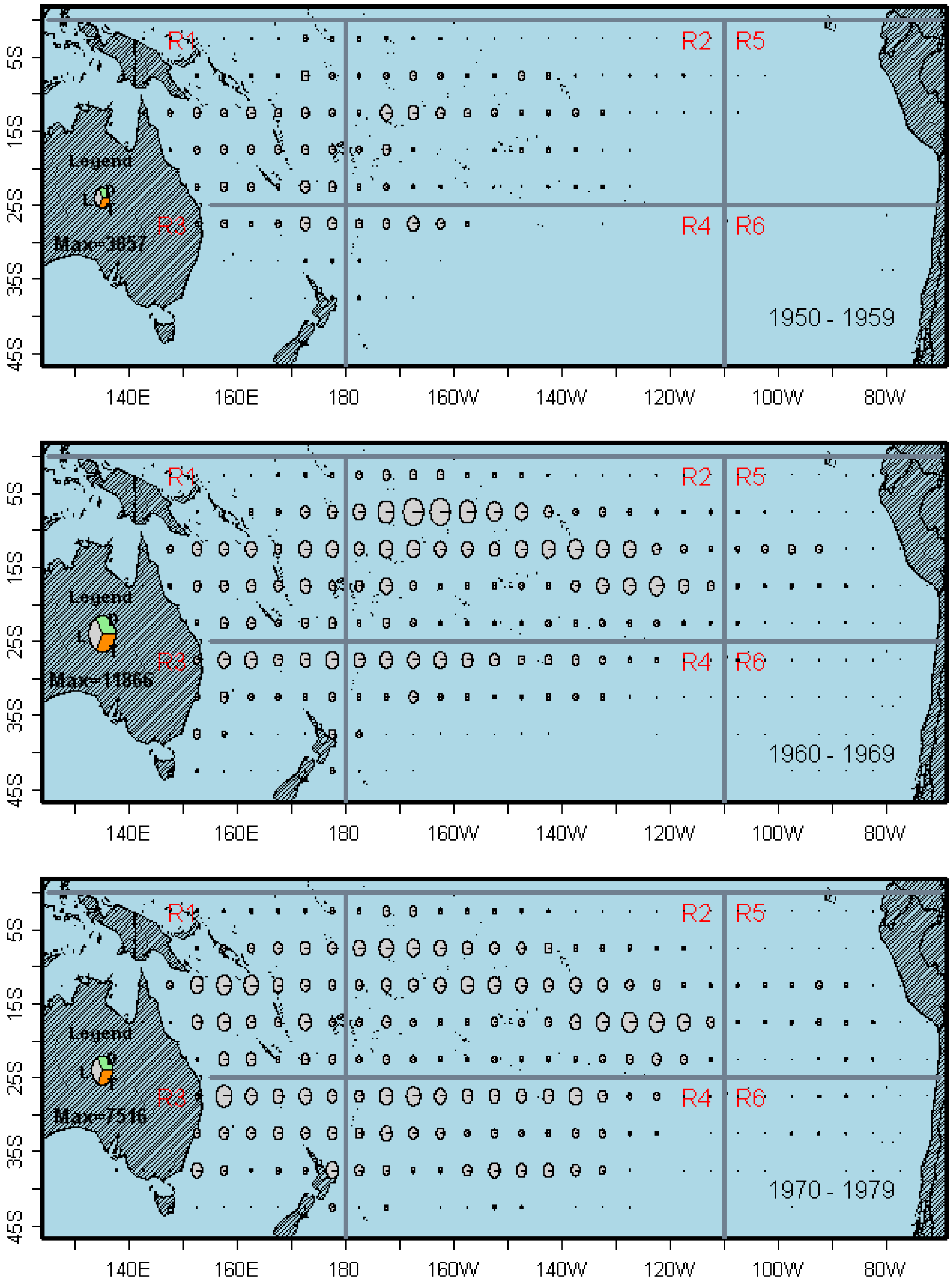


Figure 4a: Total catch by decade by 5^{0}-squares of latitude and longitude by fishing gear: longline (L), driftnet (G), and troll (T). The area of the pie chart is proportional to the total catch. The boundary of the stock assessment area is delineated by the black line and regional boundaries are delineated by grey lines.

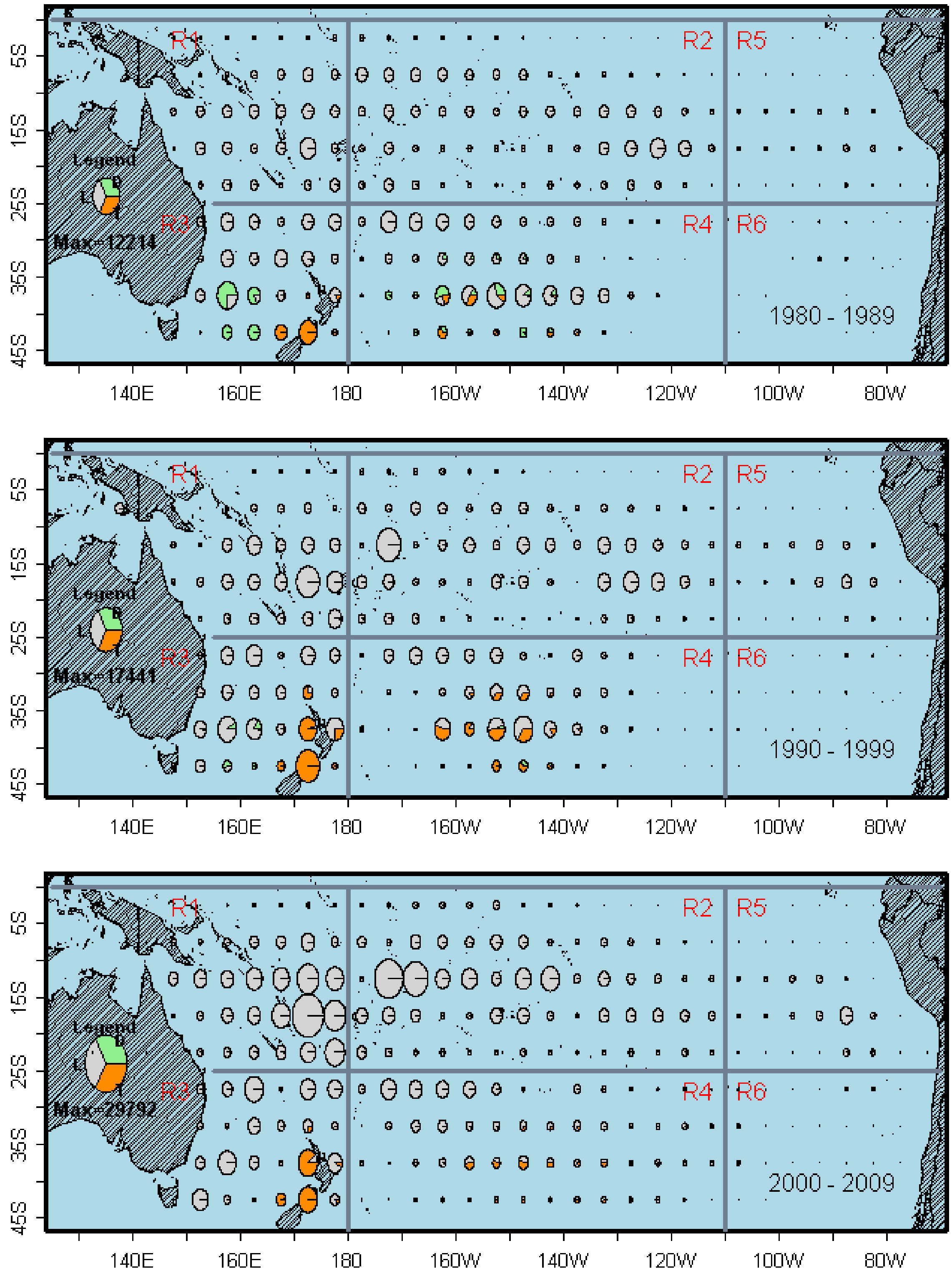


Figure 4b: Total catch by decade by 5^0-squares of latitude and longitude by fishing gear: longline (L), driftnet (G), and troll (T). The area of the pie chart is proportional to the total catch. The boundary of the stock assessment area is delineated by the black line and regional boundaries are delineated by grey lines.

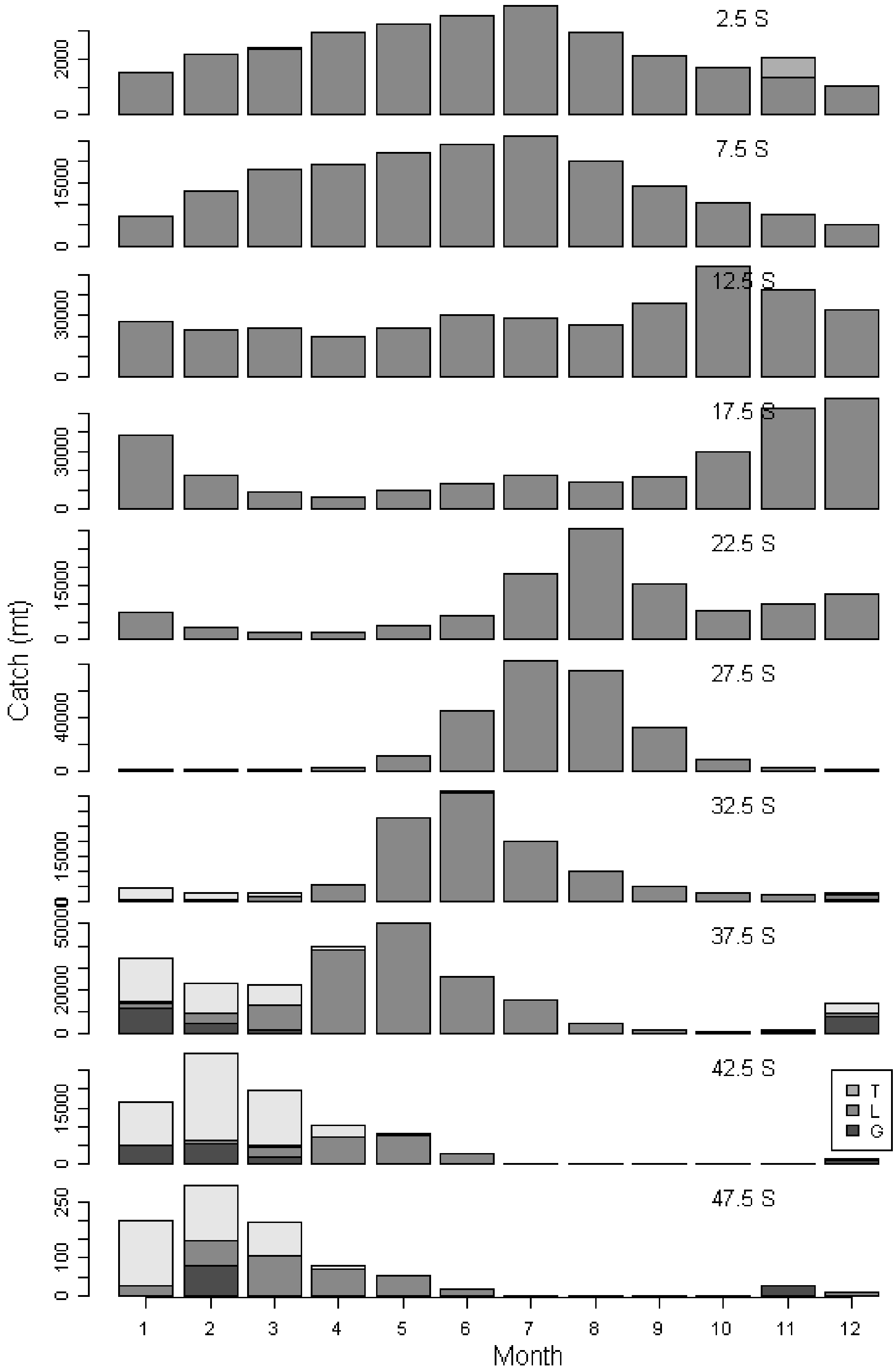


Figure 5: Cumulative monthly distribution of South Pacific albacore catch by gear (T=troll, L= longline, G=drift net) by 5^0 latitudinal band for 1980 to 2003 combined.

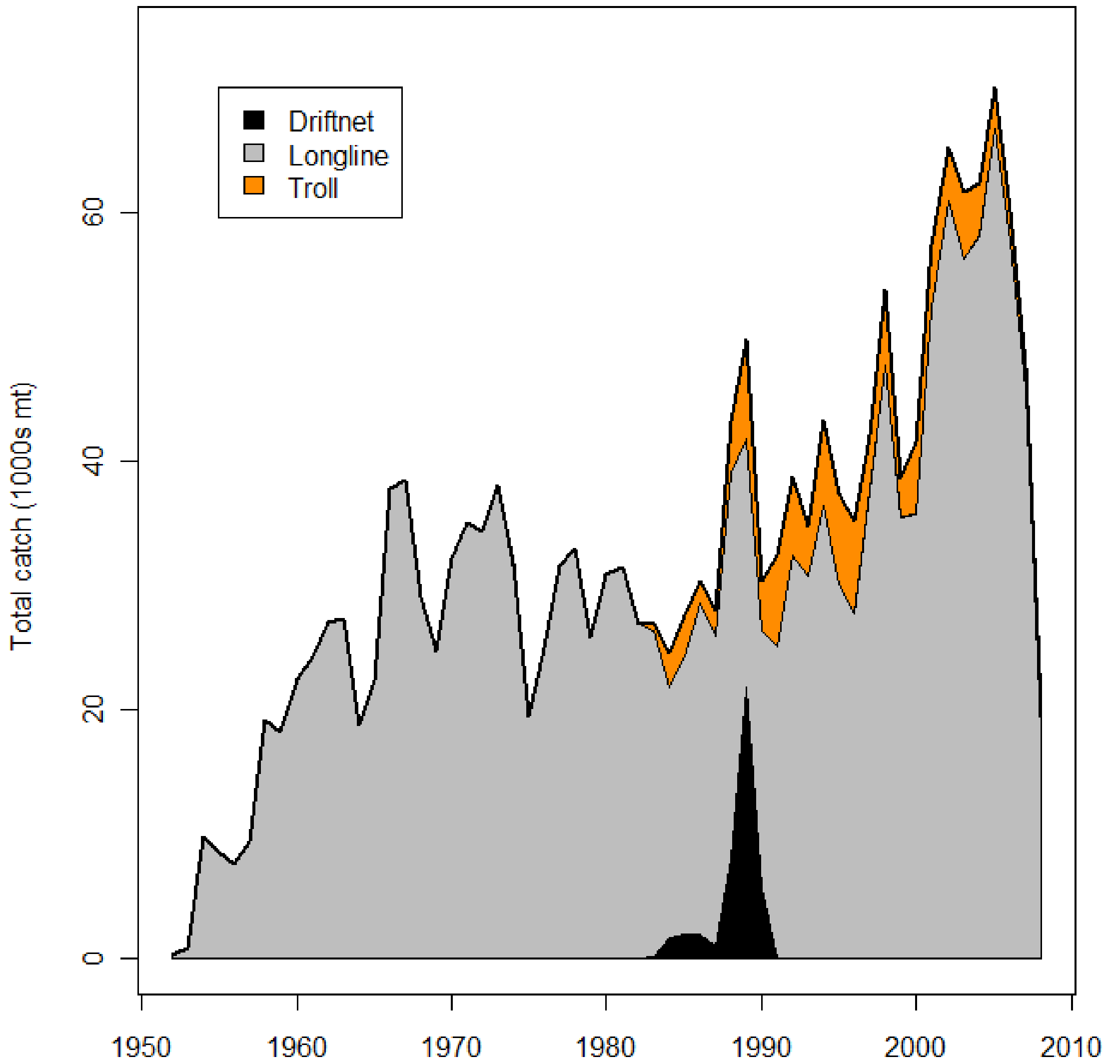


Figure 6: Total annual catch (mt) of South Pacific albacore by fishing method for 1952 to 2006.

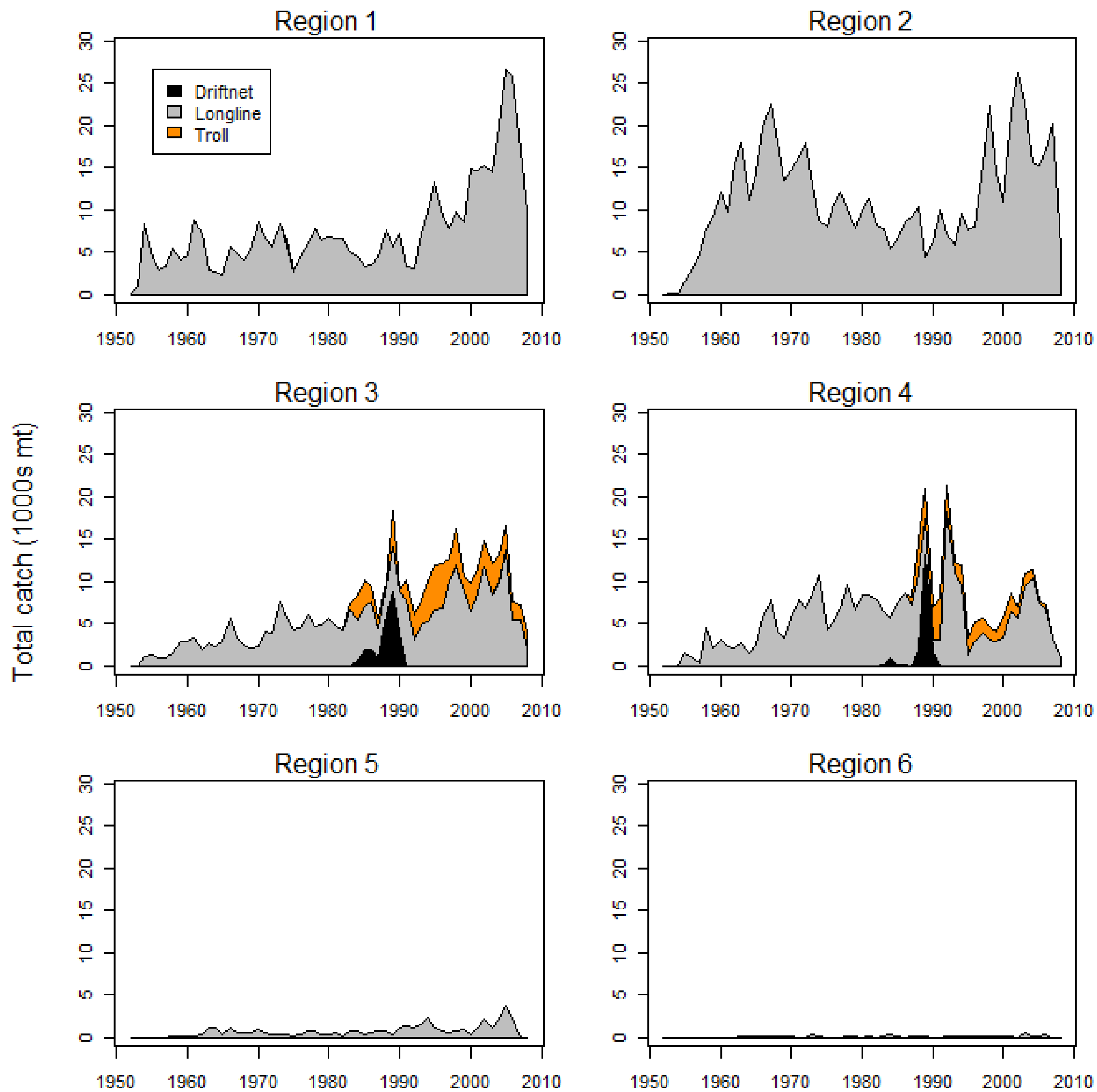


Figure 7: Total annual catch (mt) of South Pacific albacore by fishing method and region for 1952 to 2006.

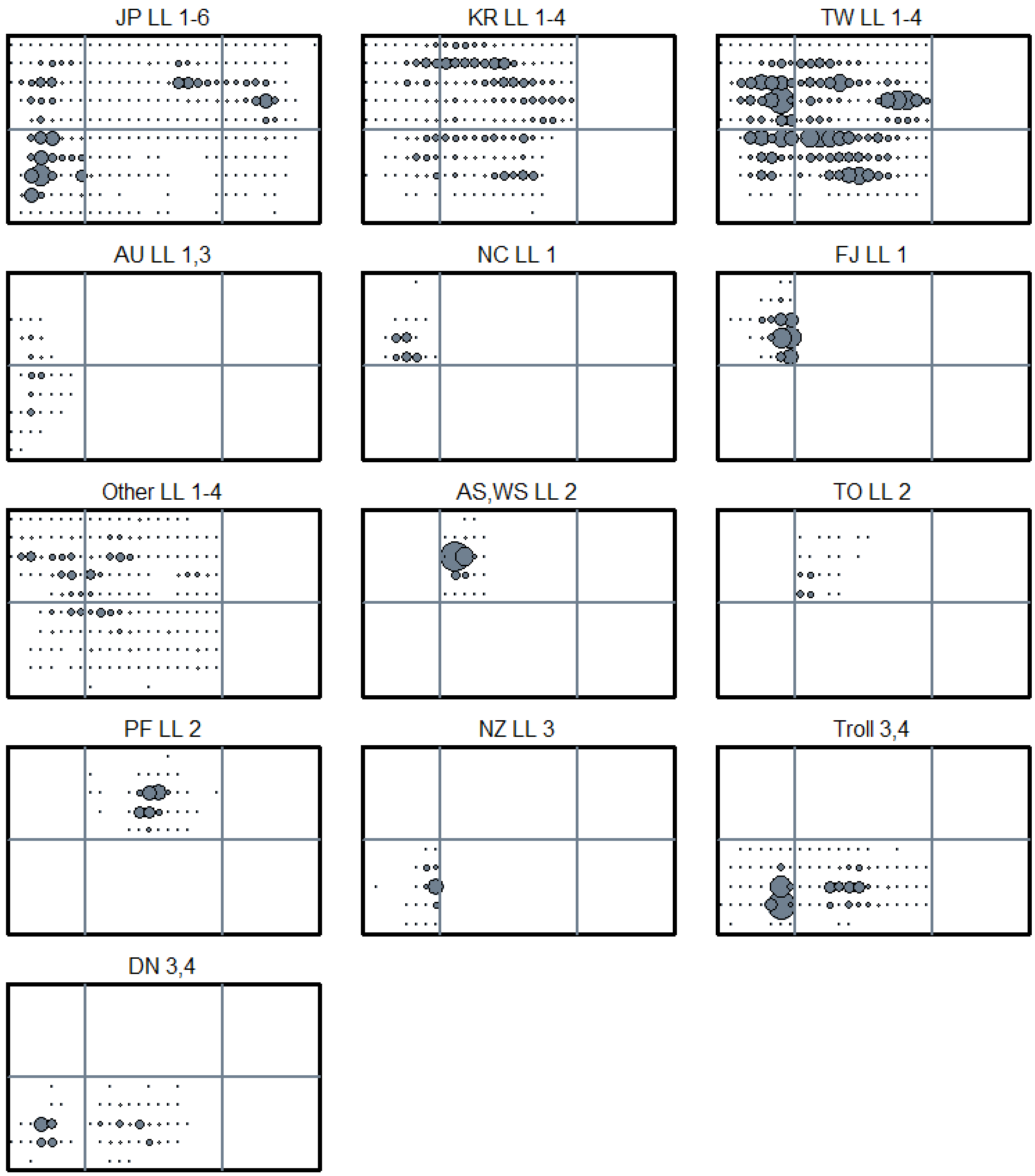


Figure 8: Cumulative albacore catch by fishery by 5^0-square of latitude and longitude from 1970 to 2008. The circle size is proportional to the cumulative catch (maximum circle size corresponds to 41,000 mt). Grey lines represent regional boundaries.

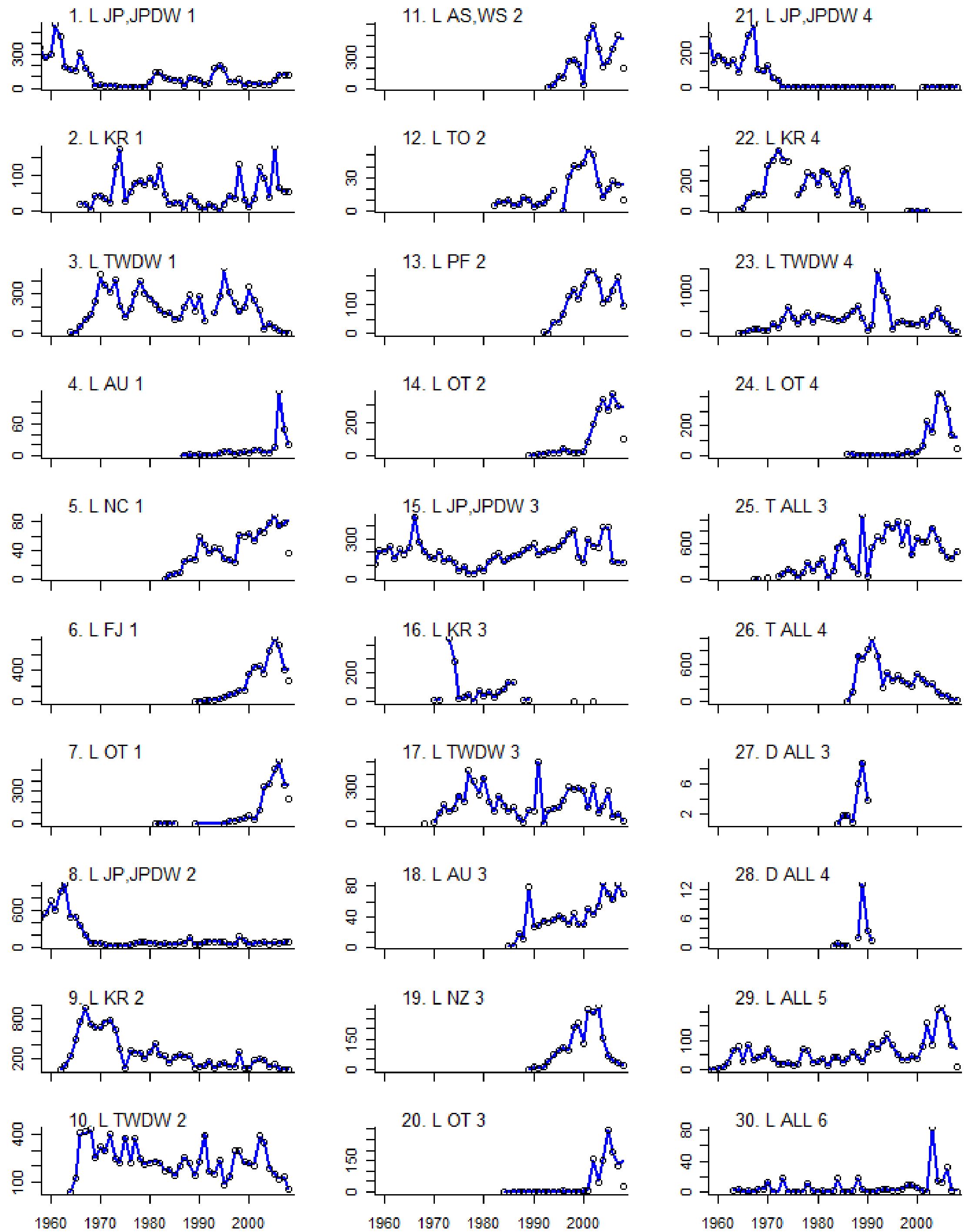


Figure 9: Annual catches (observed) by fishery (catches in thousands of fish for all fisheries except driftnet).

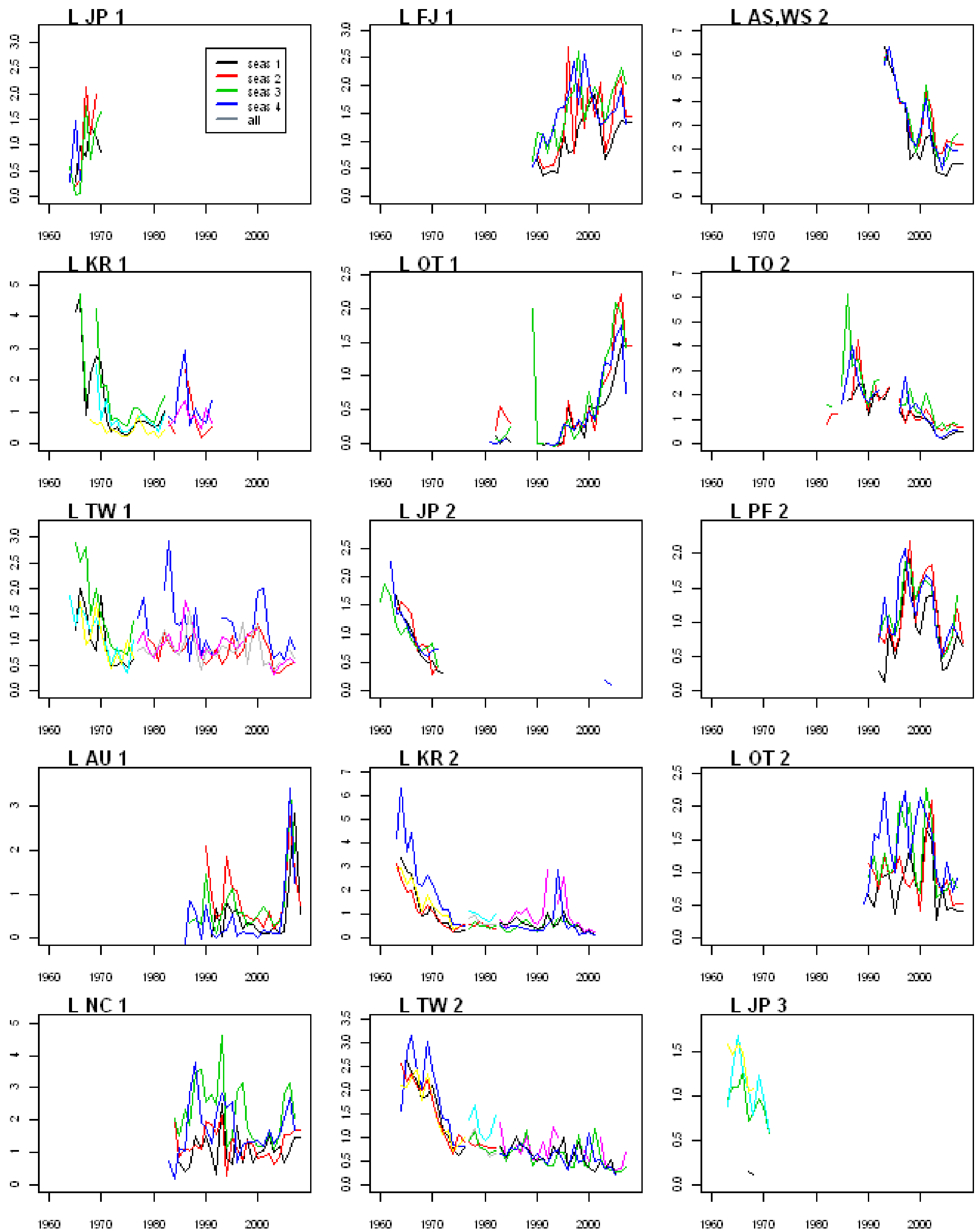


Figure 10a: Annual average catch rates by fishery. Catch rates for standardised fisheries (all JP, KR, and TW) have no units. Non-standardised longline fisheries are expressed as number per 100 hooks; troll are expressed as number per vessel·days fished; drift net are expressed as mt per day.

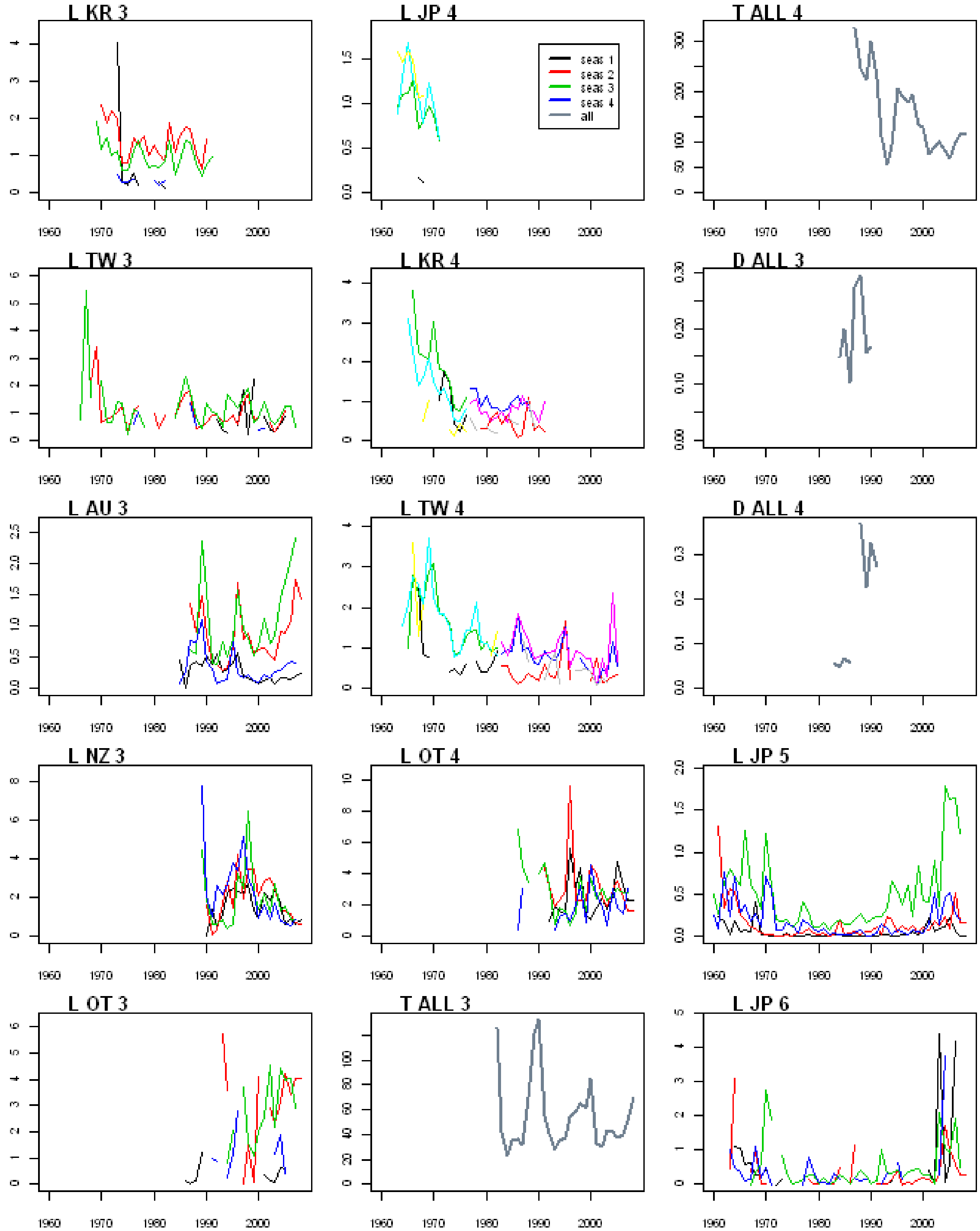


Figure 10b: Annual average catch rates by fishery. Catch rates for standardised fisheries (all JP, KR, and TW) have no units. Non-standardised longline fisheries are expressed as number per 100 hooks; troll are expressed as number per vessel·days fished; drift net are expressed as mt per day.

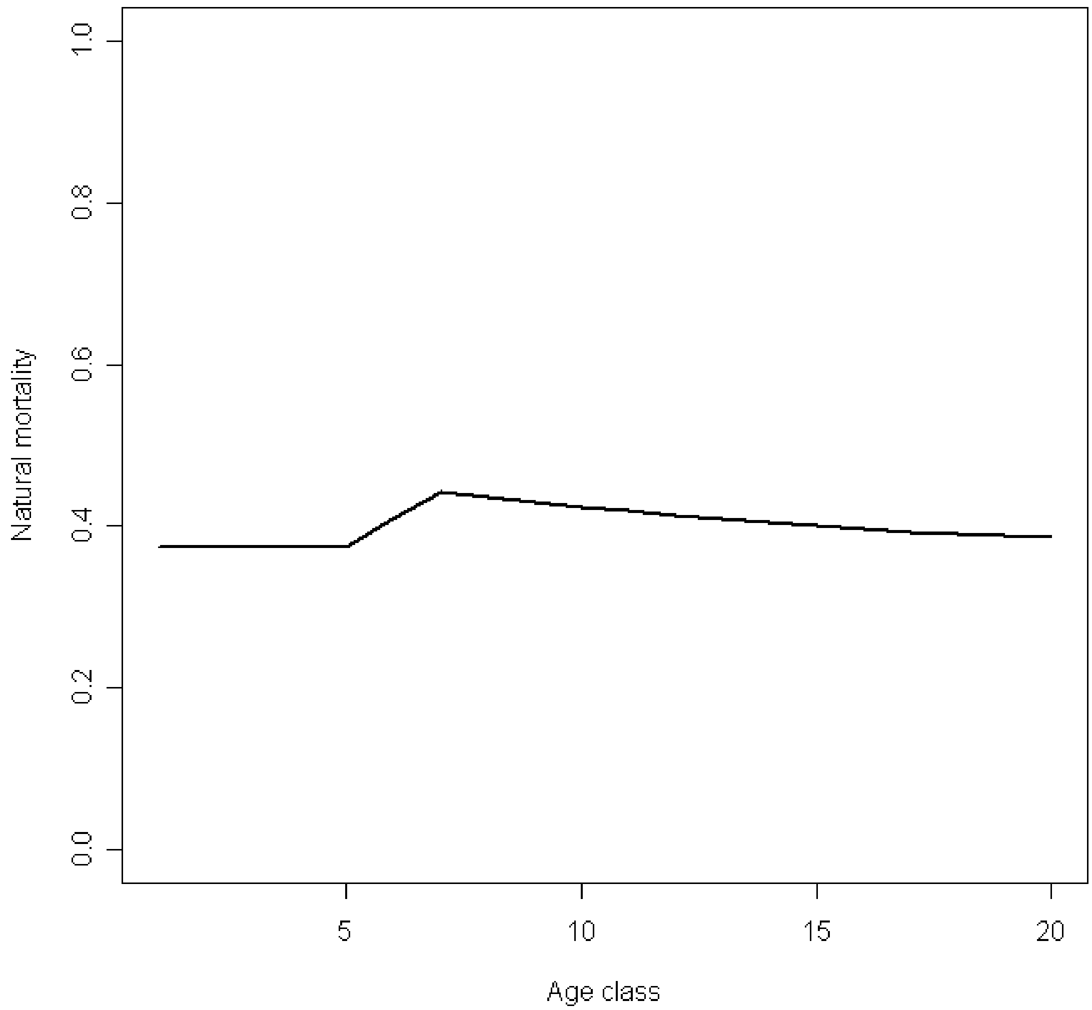


Figure 11: Natural mortality at age.

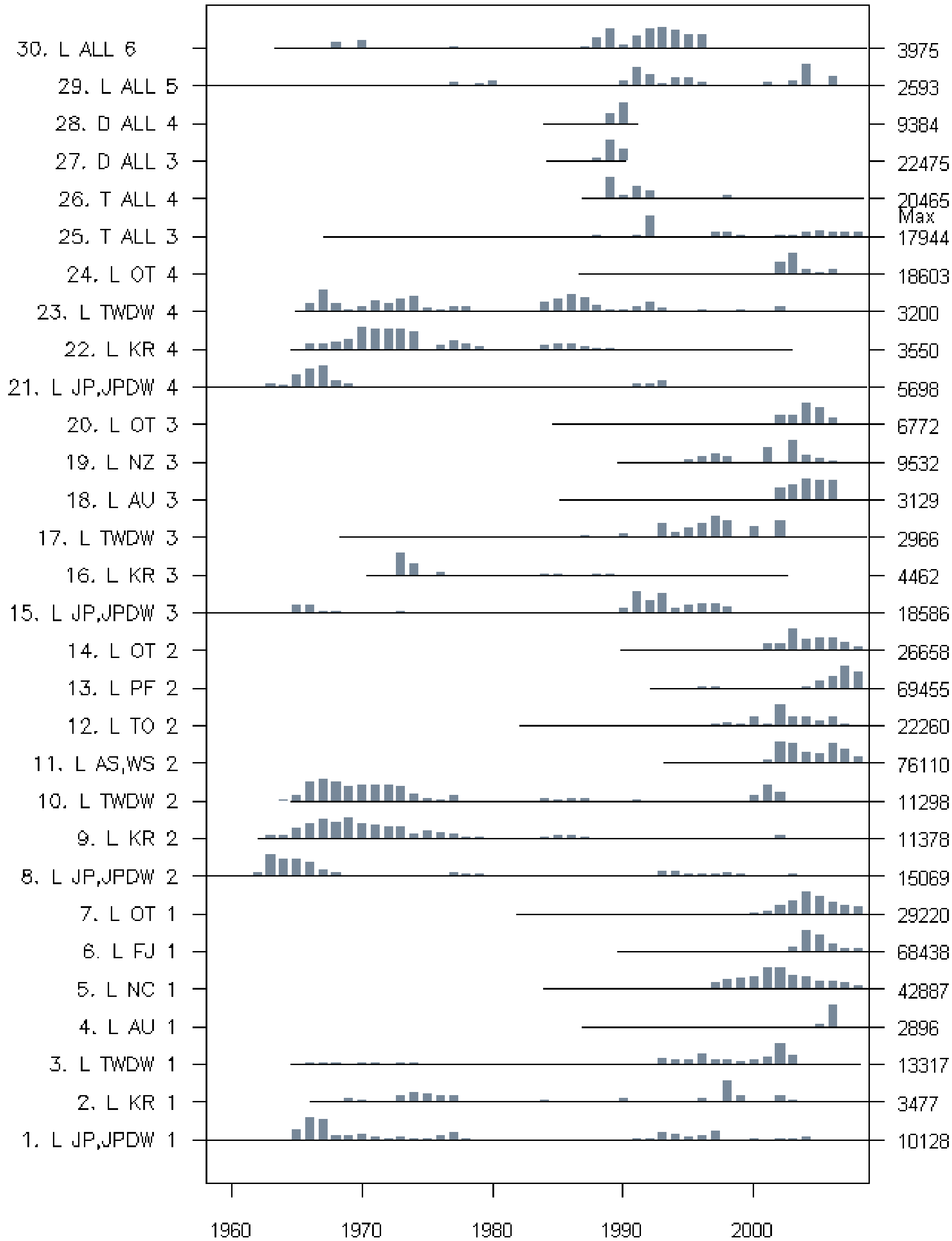


Figure 12: Length-frequency samples by fishery and year. The number on the y-axis represents the maximum number of fish measured in a single year for the fishery. Frequency histograms are scaled relative to the maximum value for the fishery. The length of the x-axis denotes the period of catch and effort data from the fishery. No size frequency data were available before 1960.

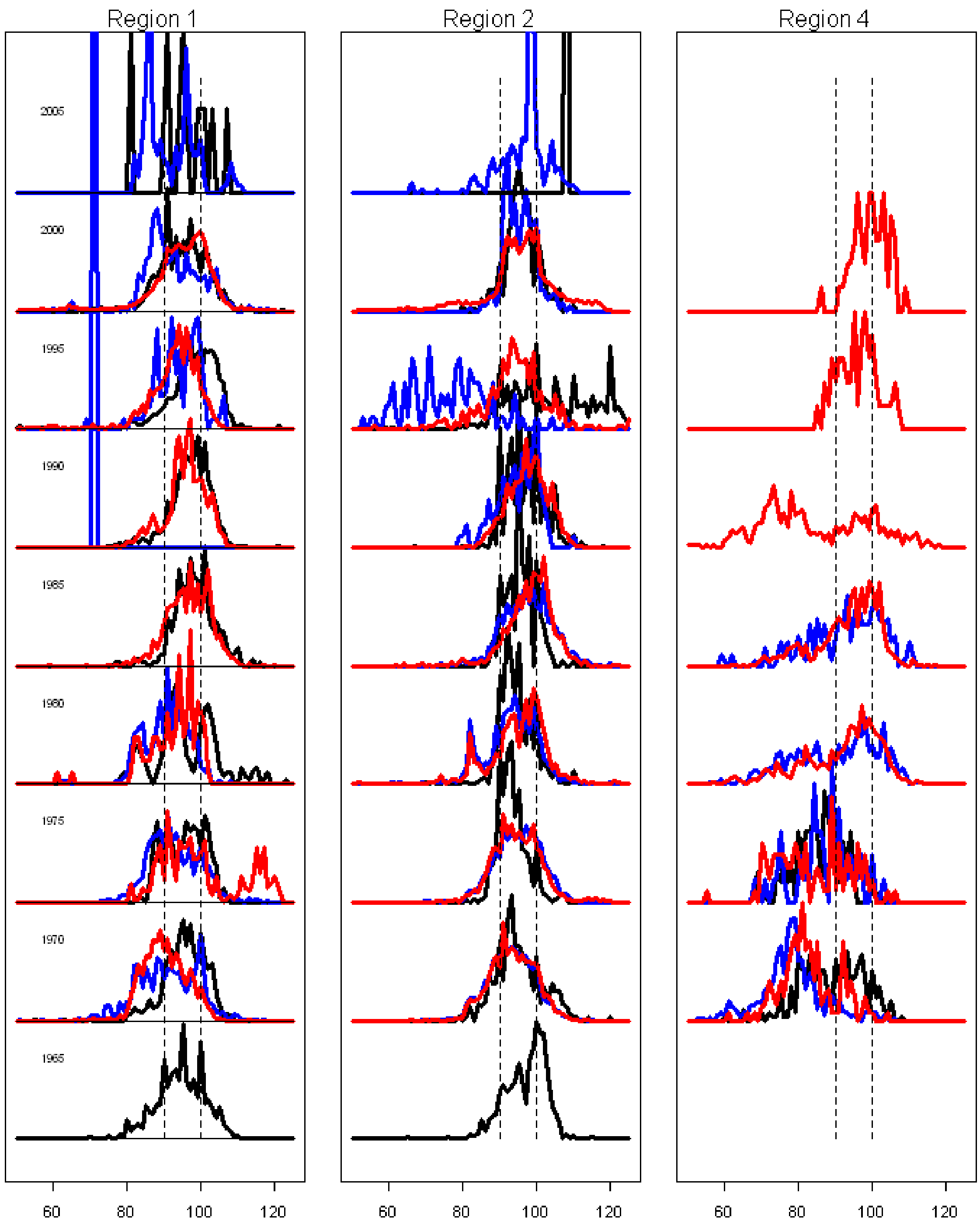


Figure 13a: Five yearly (summer) aggregated length-frequency distributions (fork length) of albacore from the Japanese (black), Korean (blue) and Chinese Taipei (red) longline fisheries in Regions 1, 2 and 4 (insufficient data were available from Region 3). The year denotes the first year of the five-year period. The two dashed vertical lines are at 90 cm and 100 cm.

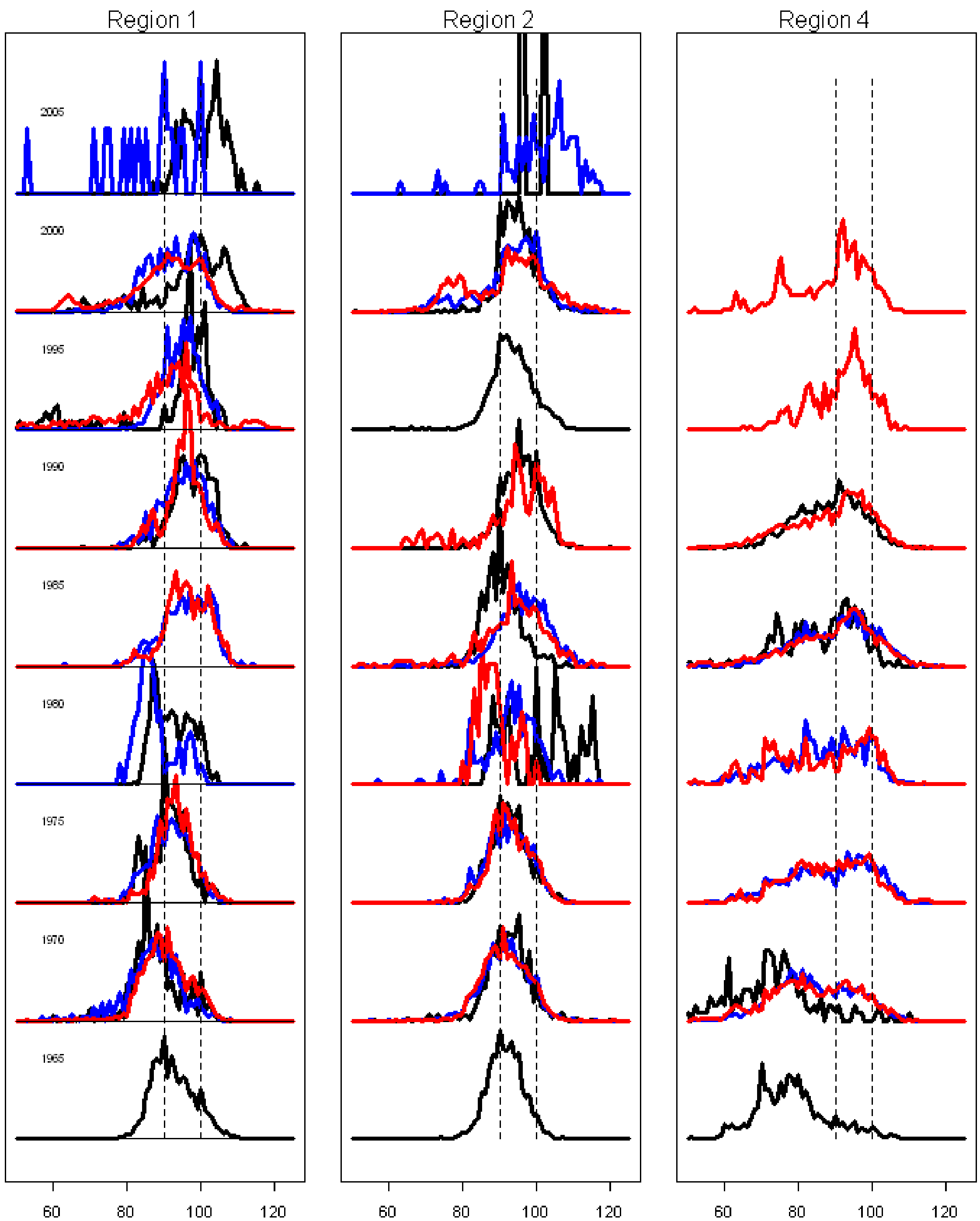


Figure 13b: Five yearly (autumn / fall) aggregated length-frequency distributions (fork length) of albacore from the Japanese (black), Korean (blue) and Chinese Taipei (red) longline fisheries in Regions 1, 2 and 4 (insufficient data were available from Region 3). The year denotes the first year of the five-year period. The two dashed vertical lines are at 90 cmand 100 cm.

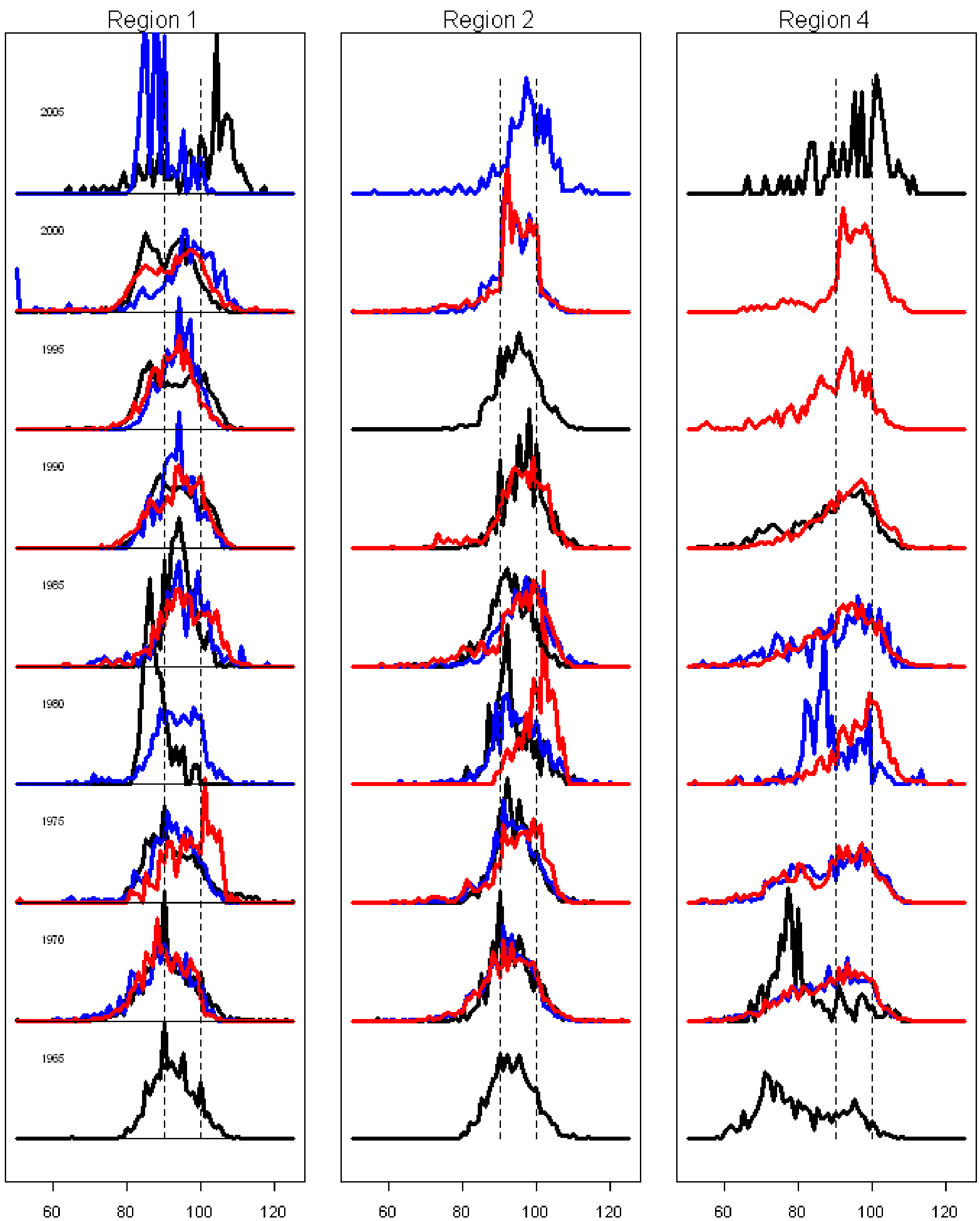


Figure 13c: Five yearly (winter) aggregated length-frequency distributions (fork length) of albacore from the Japanese (black), Korean (blue) and Chinese Taipei (red) longline fisheries in Regions 1, 2 and 4 (insufficient data were available from Region 3). The year denotes the first year of the five-year period. The two dashed vertical lines are at 90 cm and 100 cm.

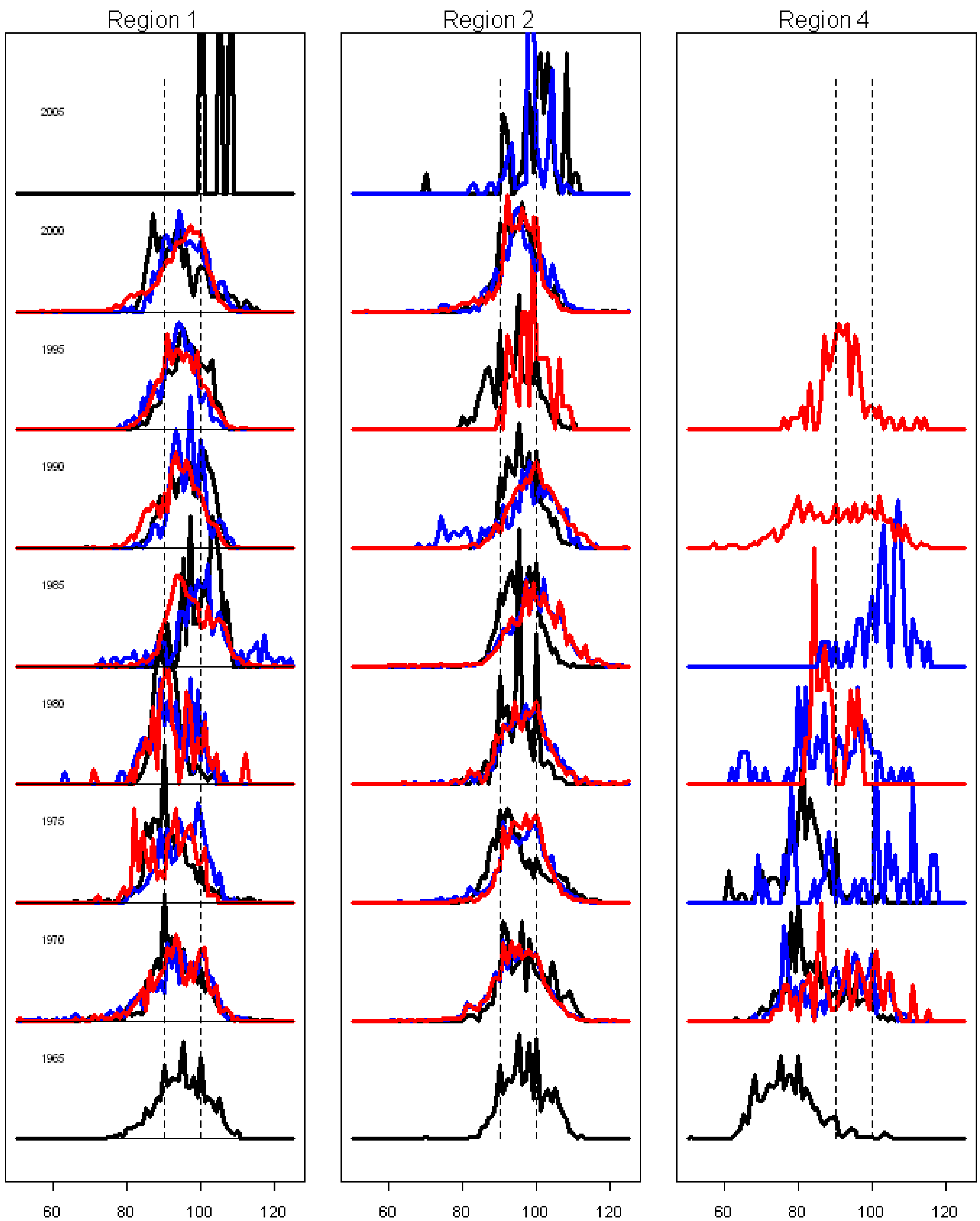


Figure 13d: Five yearly (spring) aggregated length-frequency distributions (fork length) of albacore from the Japanese (black), Korean (blue) and Chinese Taipei (red) longline fisheries in Regions 1, 2 and 4 (insufficient data were available from Region 3). The year denotes the first year of the five-year period. The two dashed vertical lines are at 90 cm and 100 cm.

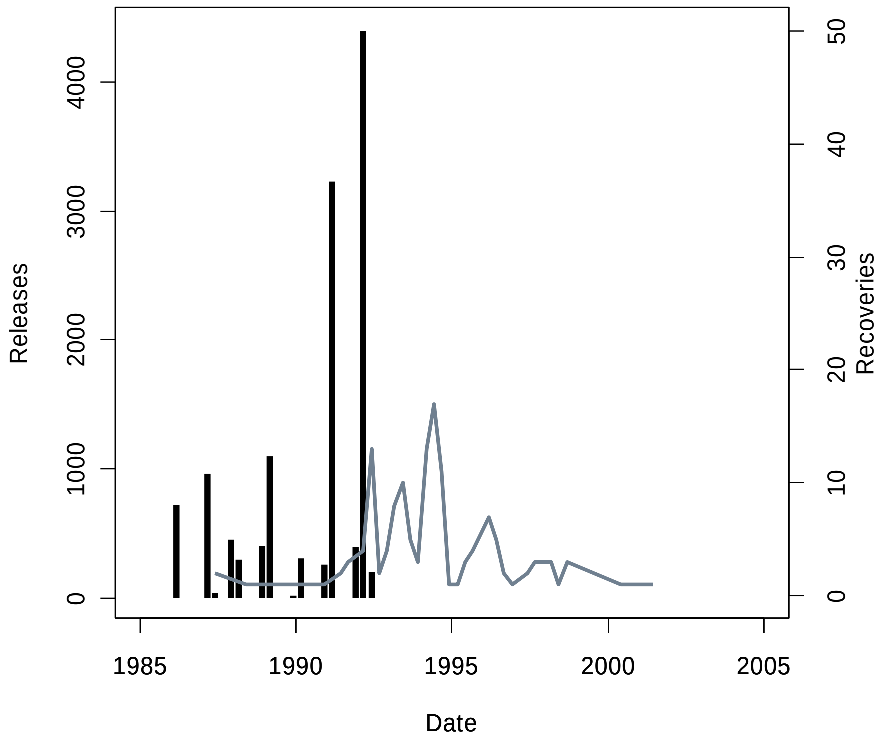


Figure 14: Tag releases (bars) and recoveries (line) by quarter for the South Pacific albacore fishery.

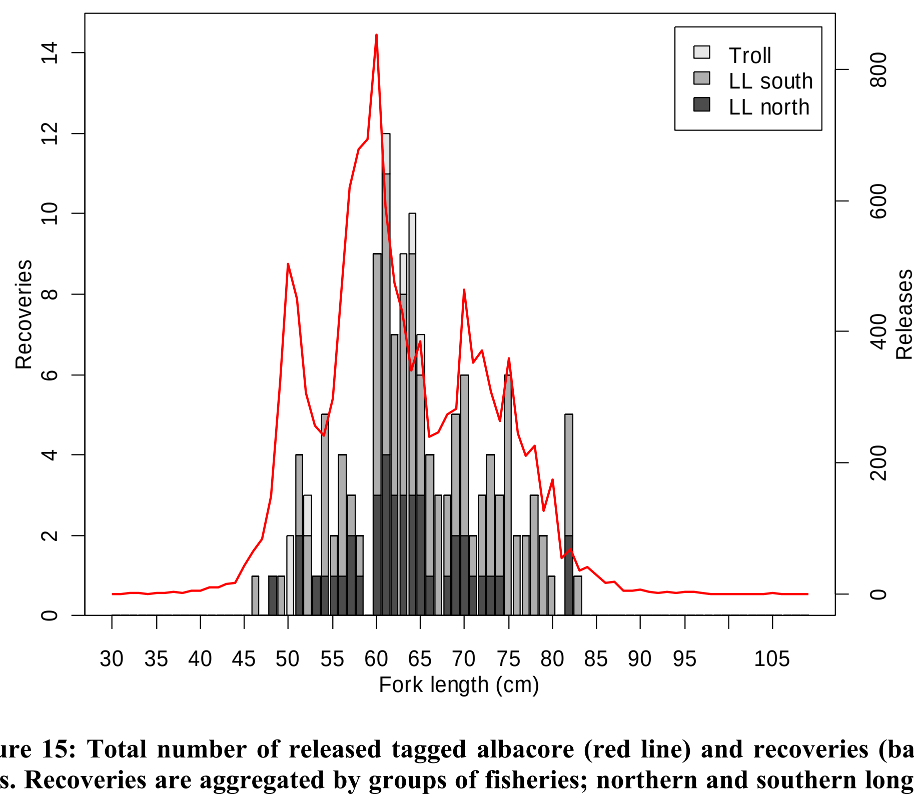


Figure 15: Total number of released tagged albacore (red line) and recoveries (bar plot) by length class. Recoveries are aggregated by groups of fisheries; northern and southern longline fisheries and troll fisheries.

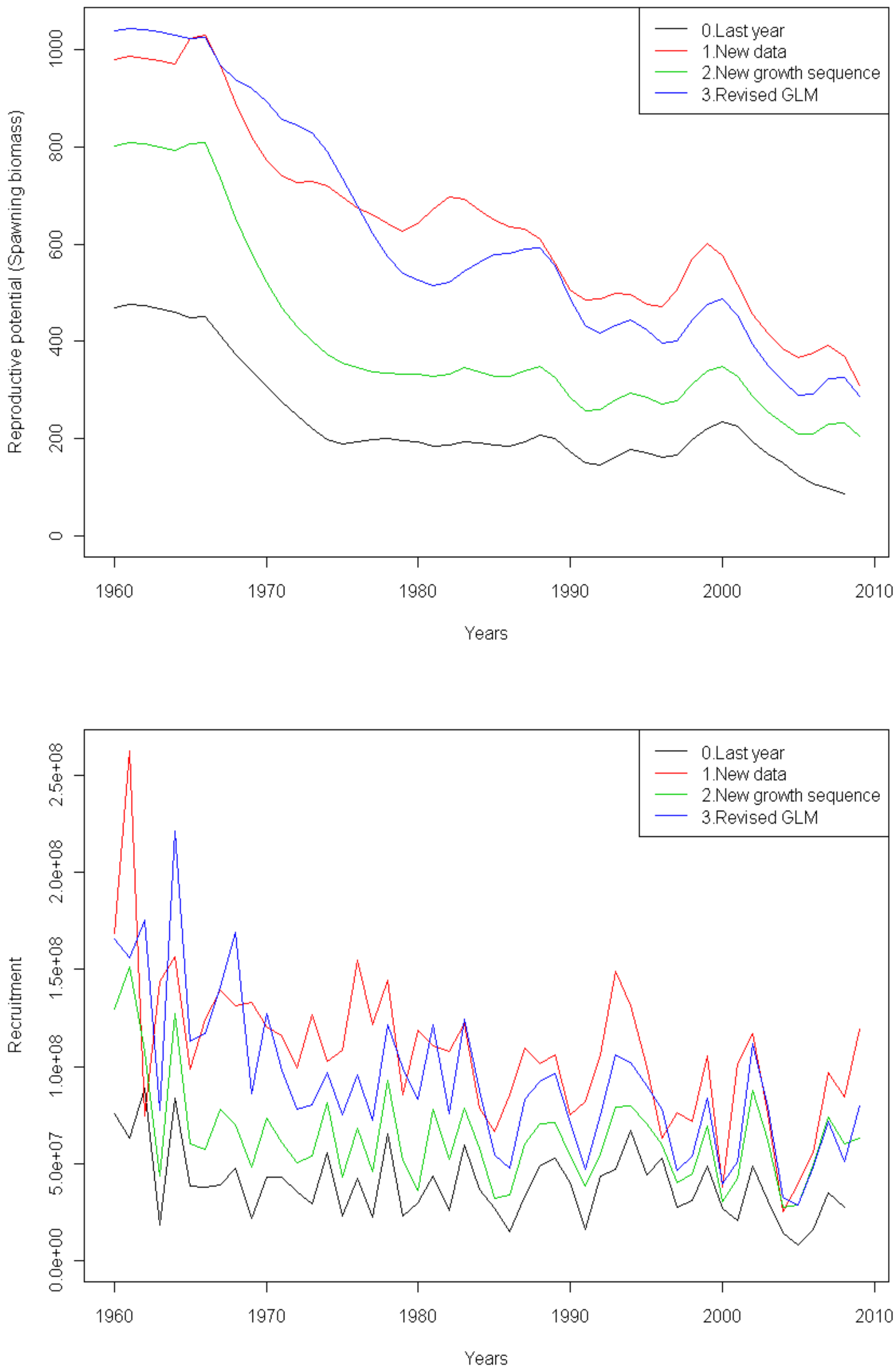


Figure 16: Structural comparison 1: Annual trends in spawning biomass and relative recruitment from models with the following progressive changes: 0) the same setup as in 2008, 1) model 0 with data updated to the end of 2008, 2) model 1 with a new MFCL batch (doitall) file and sequence of growth estimation, and 3) model 2 with the new standardized CPUE series (Bigelow & Hoyle 2009).

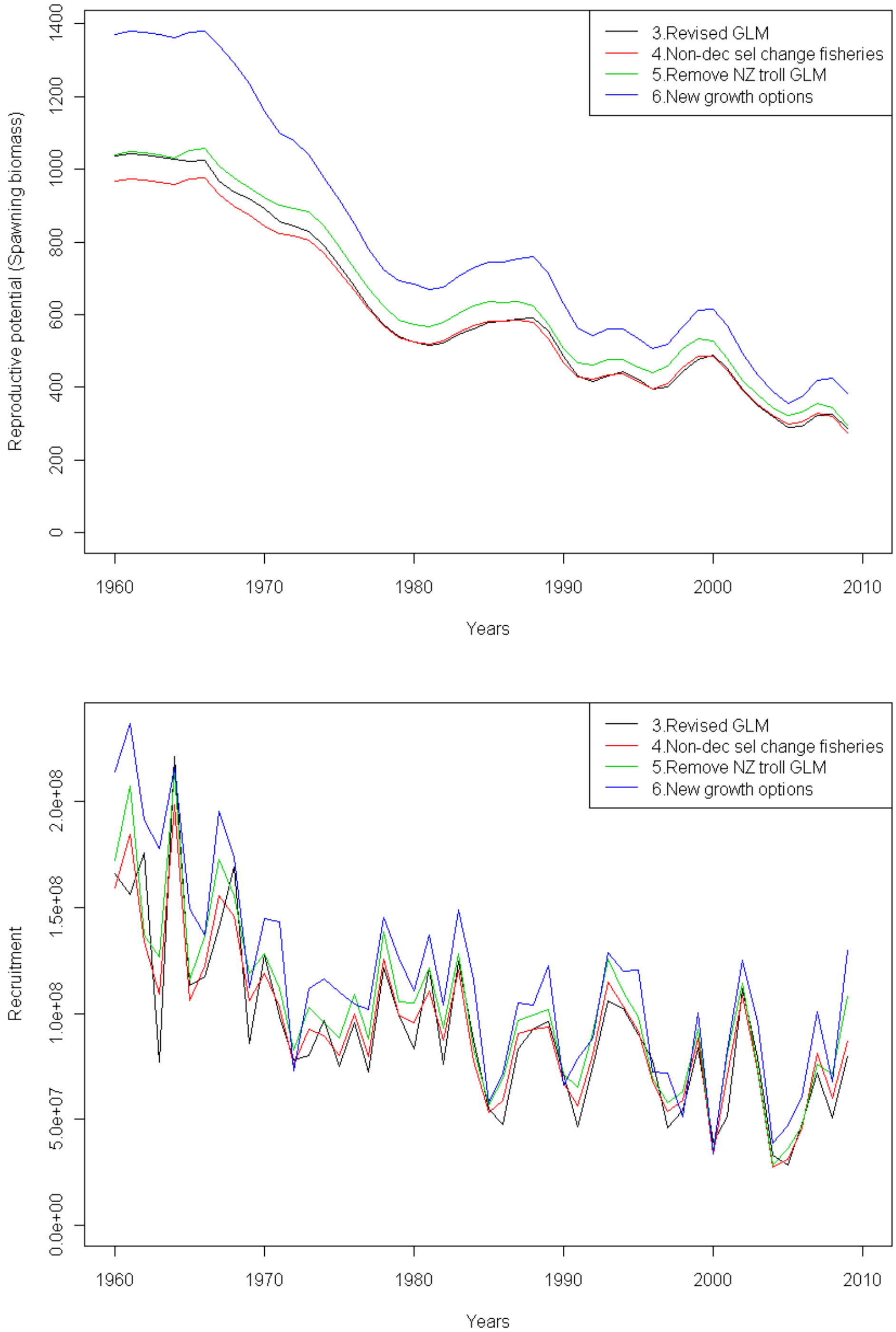
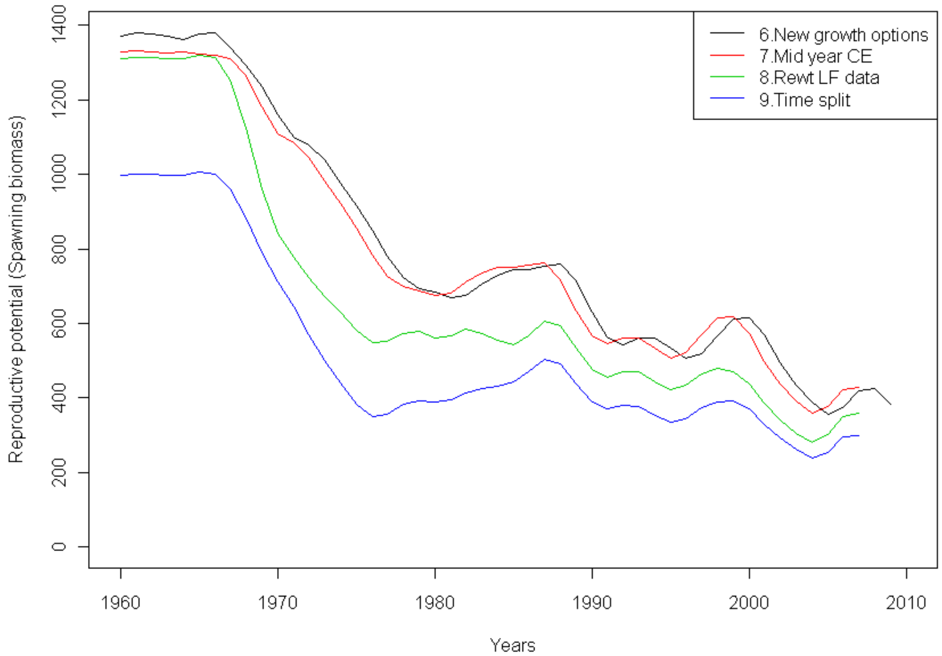


Figure 17: Structural comparison 2: Annual trends in adult biomass and relative recruitment from four models: 3) the revised GLM as above, 4) model 3 with non-decreasing selectivity imposed on three fisheries, 5) model 4 without the assumption that the standardized CPUE from the New Zealand troll fishery indexes abundance, and 6) model 5 with new growth options including the estimation of growth offsets.



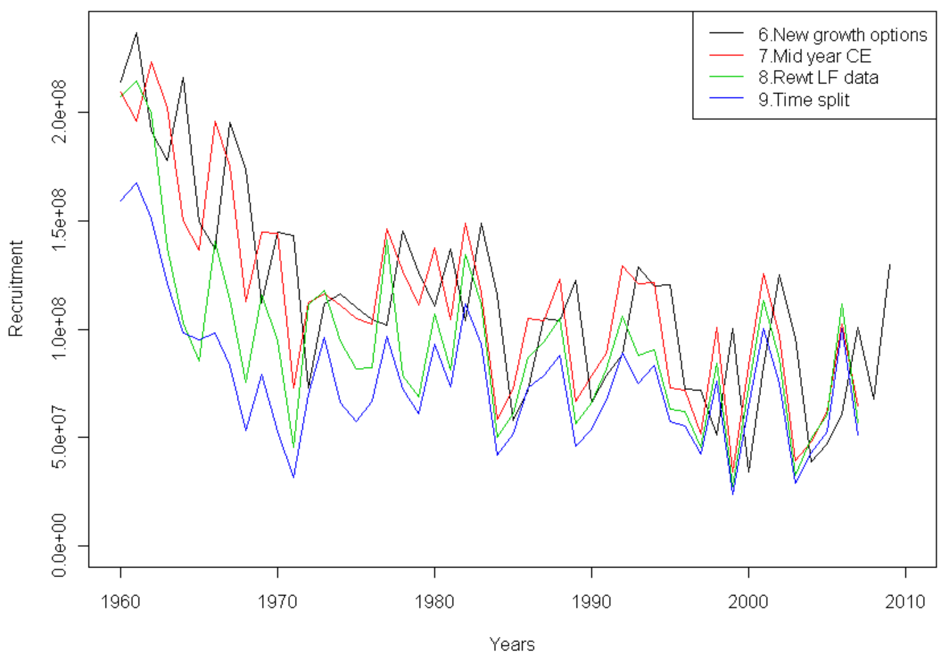
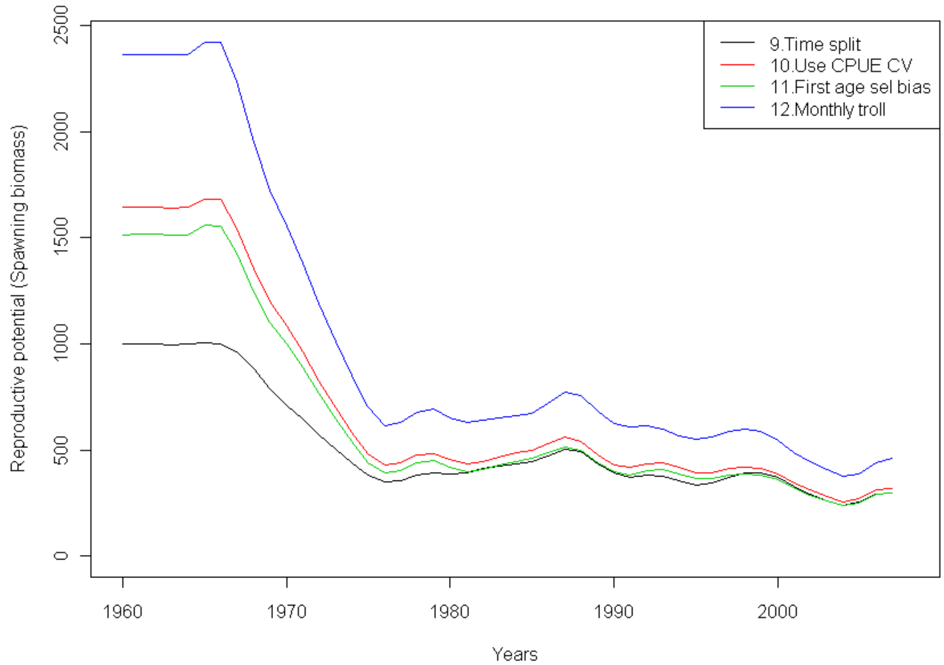


Figure 18: Structural comparison 3: Annual trends in adult biomass and relative recruitment from four models: 6) the new growth options as above, 7) model 6 after removing catch data from the first half of 1960 and the second half of 2008, 8) model 7 after reweighting the size data from most fisheries, 9) model 8 after adding time splits to the selectivity of many of the distant water longline fisheries.



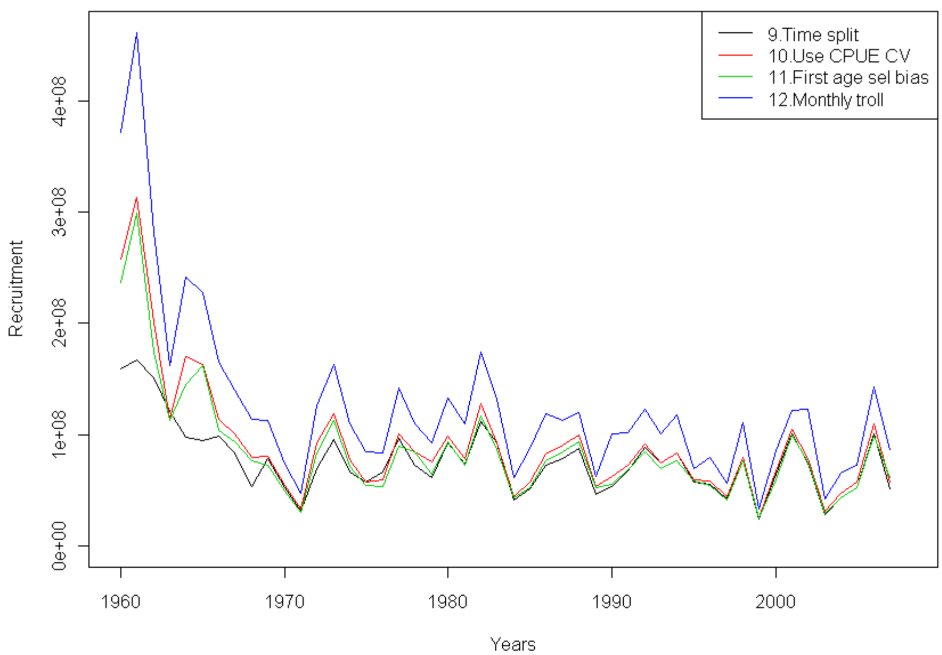
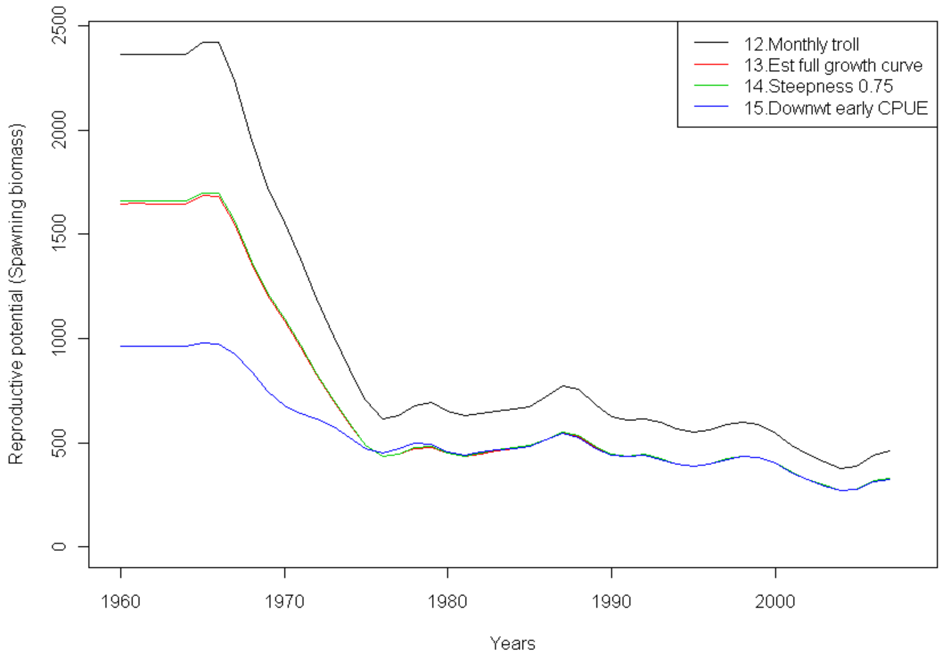


Figure 19: Structural comparison 4: Annual trends in adult biomass and relative recruitment from four models: 9) with time split fisheries as above, 10) model 9 using the CV's estimated in the CPUE standardization to penalize the time series, 11) model 10 estimating a selectivity bias to account for partial recruitment of young fish to the troll fisheries, and 12) model 11 with a monthly time step applied to the troll and driftnet fisheries.



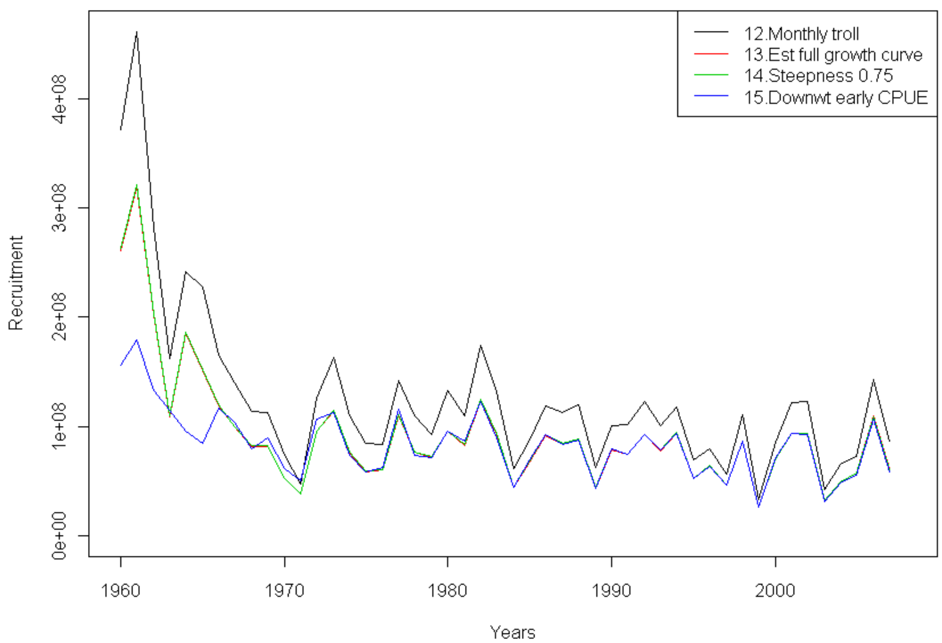
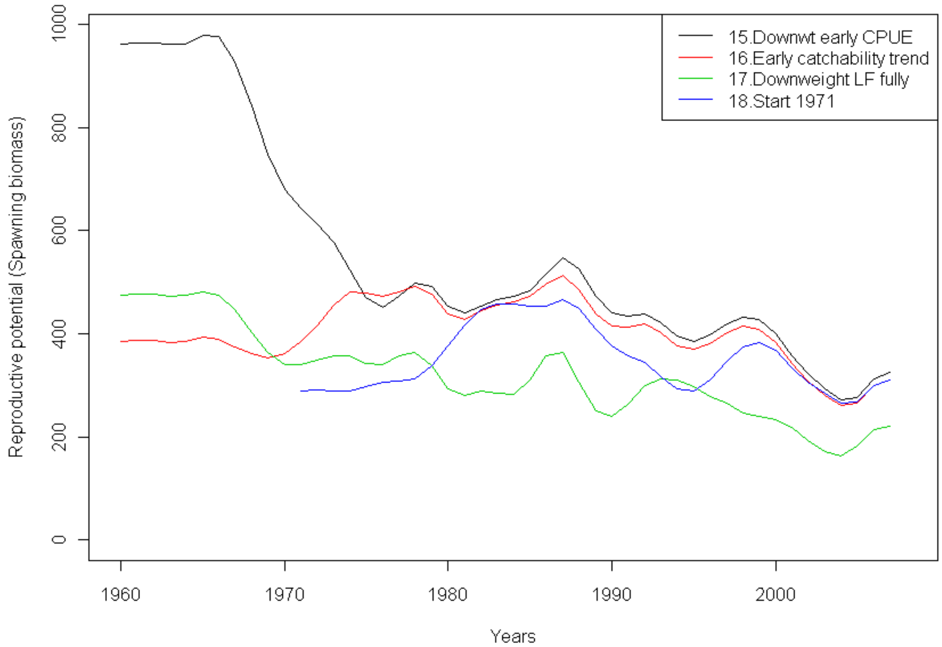


Figure 20: Structural comparison 5: Annual trends in adult biomass and relative recruitment from four models: 12) with a monthly time step for small fish fisheries as above, 13) model 12 with full estimation of the growth curve, 14) model 13 with steepness of 0.75 instead of 0.9, and 15) model 14 with the weight given to CPUE data before 1971 reduced by 1/100.



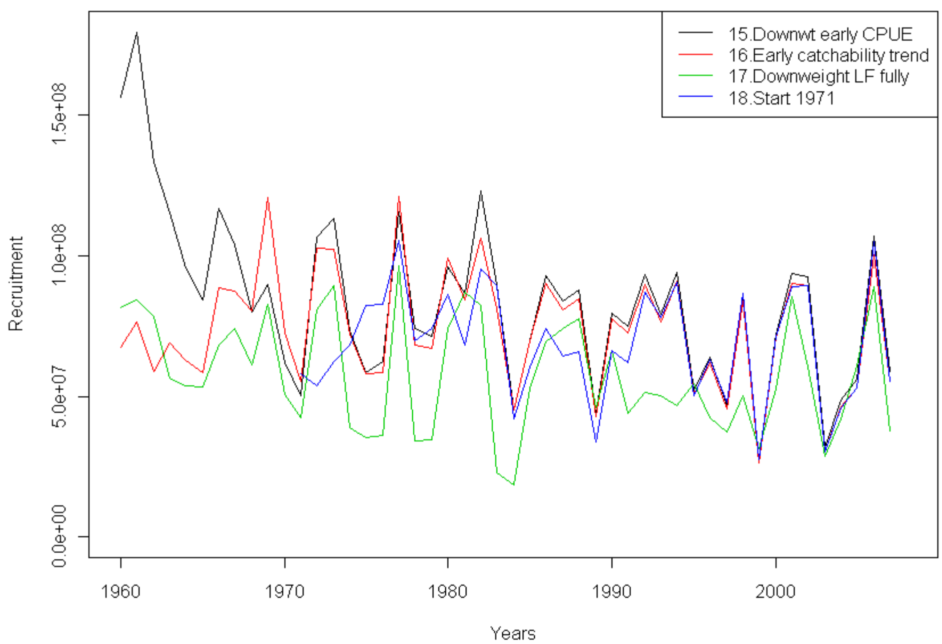


Figure 21: Scenario comparison: Annual trends in adult biomass and relative recruitment from four models: 15) Early CPUE data down-weighted as above, 16) model 15 with time-varying catchability estimated for the earliest part of the time series, 17) model 16 with the length frequency data fully down-weighted, and 18) as for model 14 but starting in 1971.

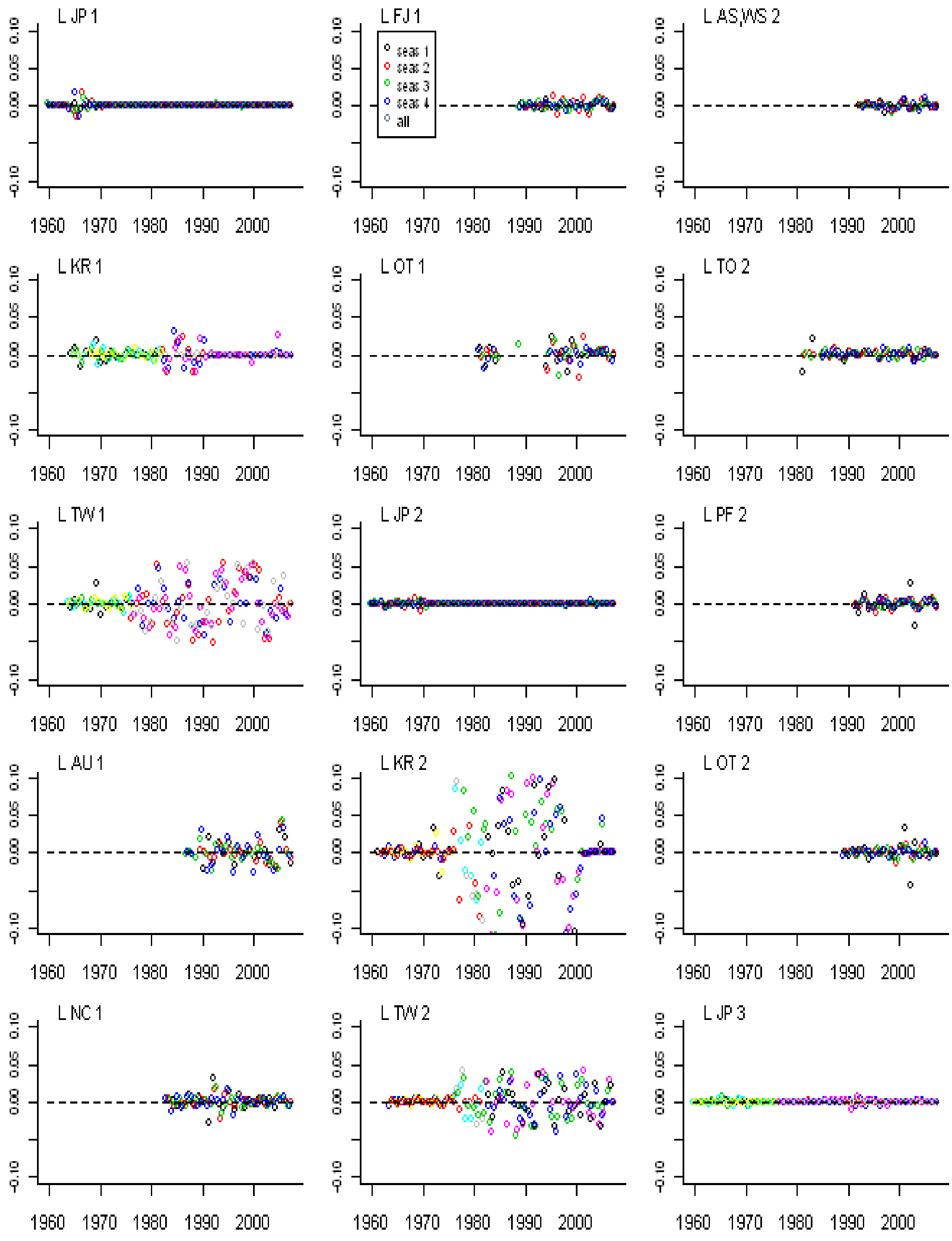


Figure 22a: Residuals of ln (total catch) for each fishery.

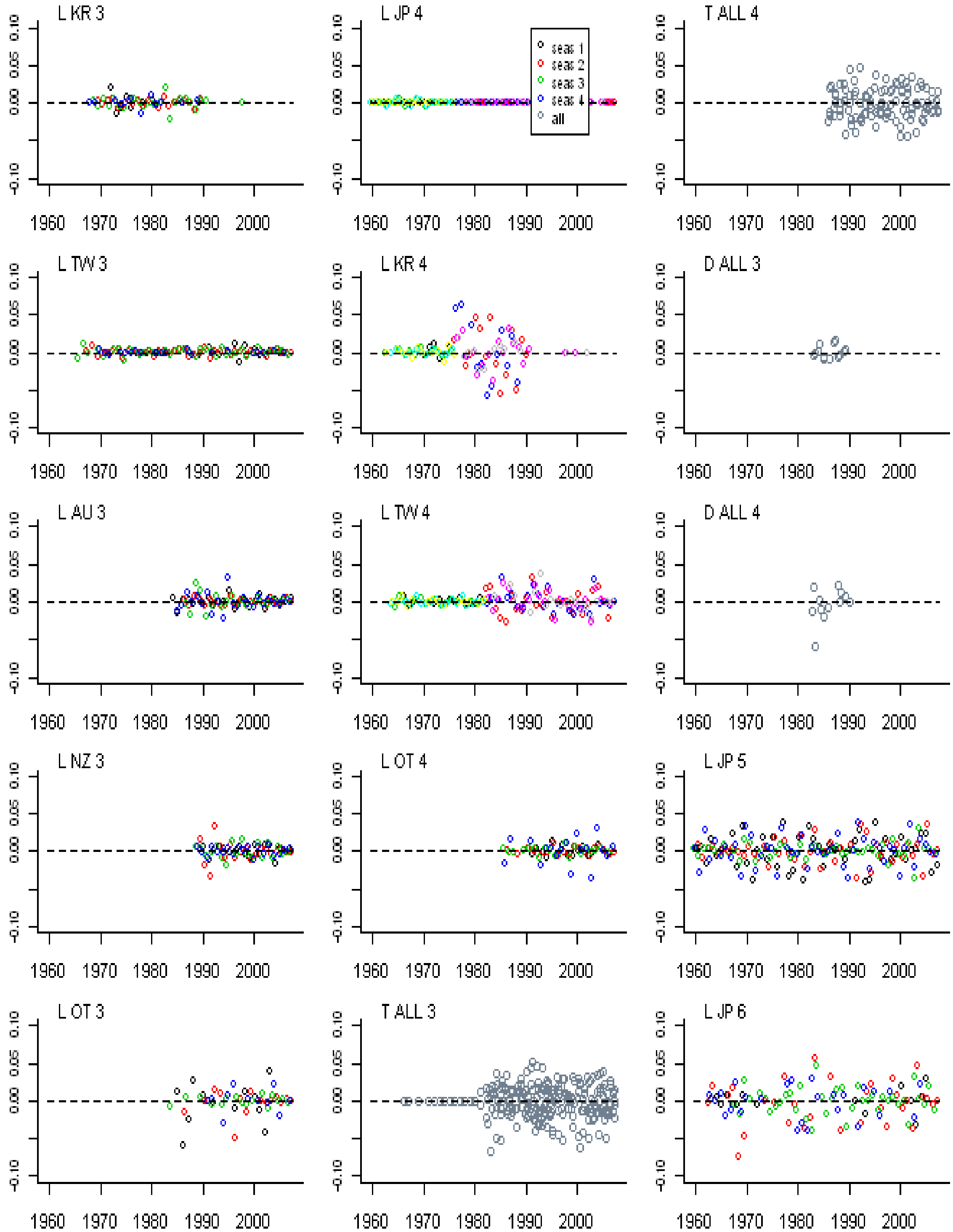


Figure 22b: Residuals of ln (total catch) for each fishery.

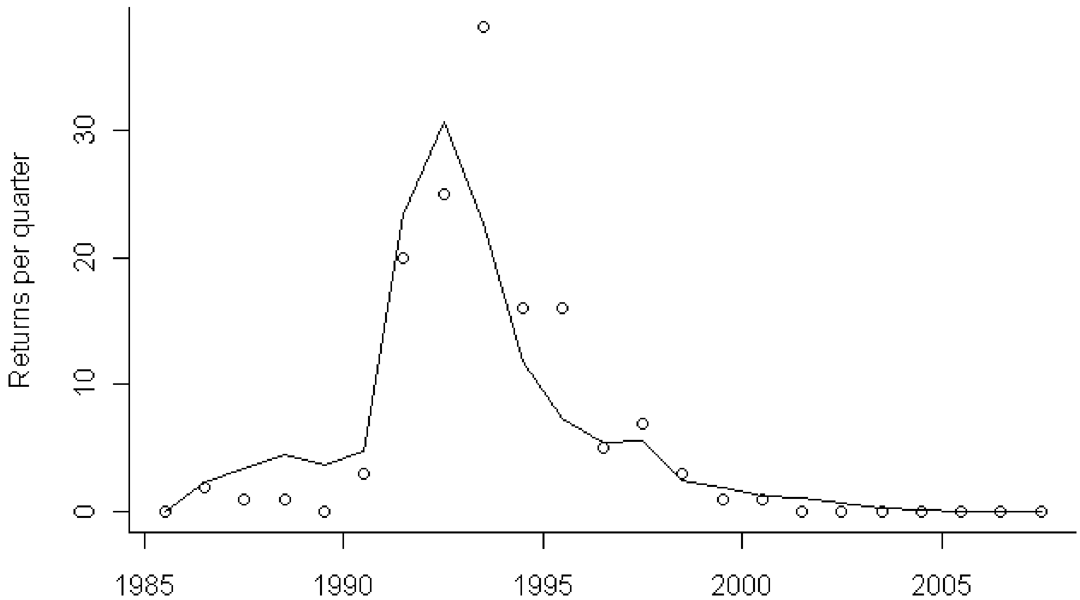


Figure 23: A comparison of observed (points) and predicted (line) number of annual tag returns from the South Pacific albacore fishery.

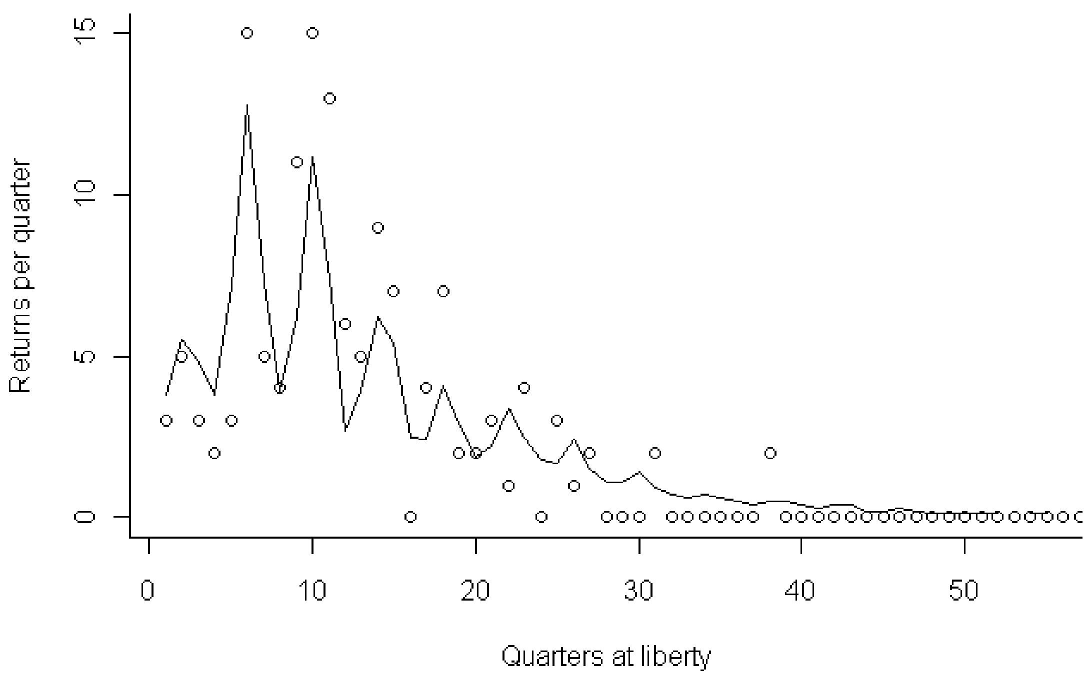


Figure 24: A comparison of observed (points) and predicted (line) number of tag returns by period at liberty (quarters) from the South Pacific albacore fishery.

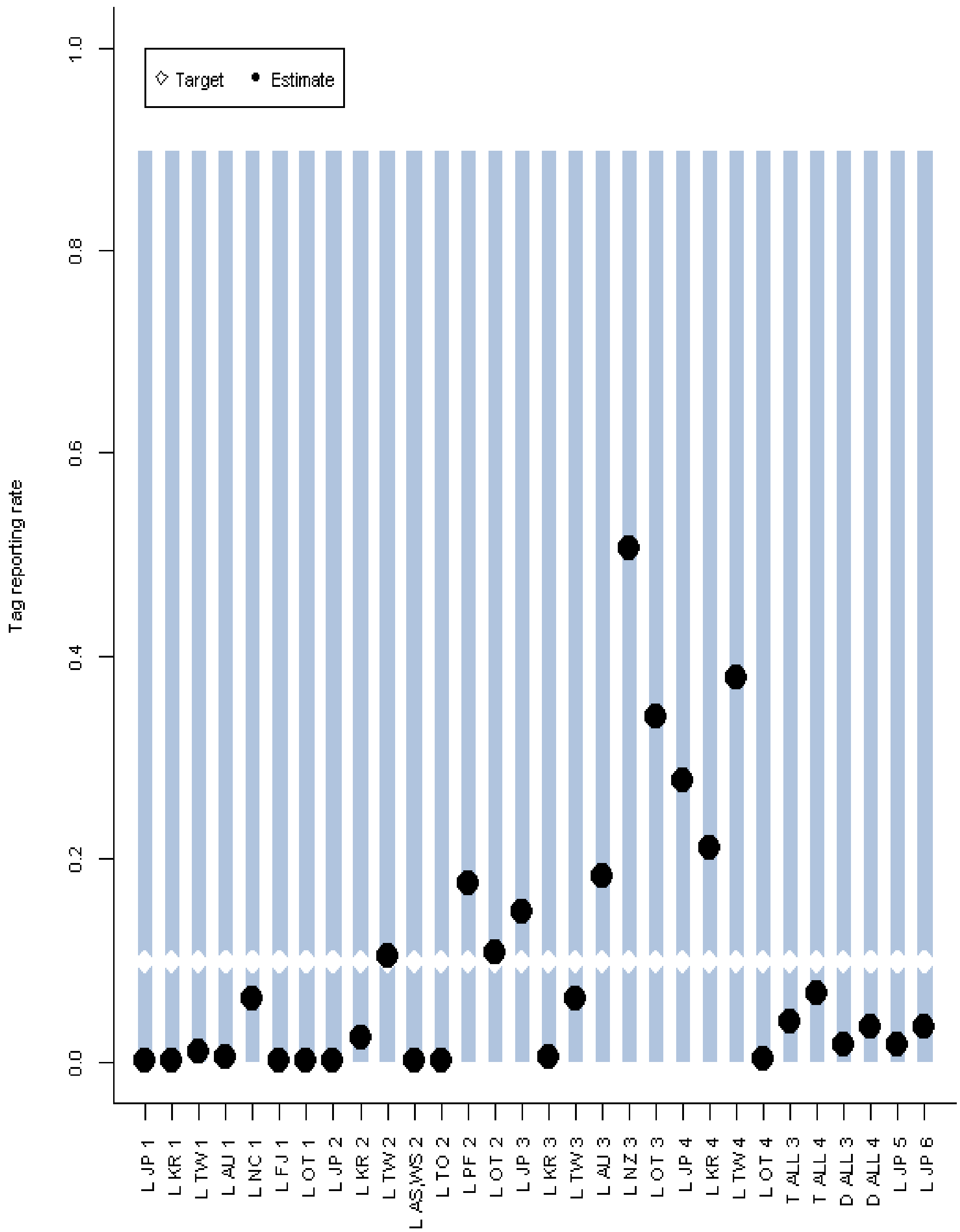


Figure 25: Estimated tag-reporting rates by fishery (black circles). White diamonds indicate the modes of the priors for each reporting rate, and grey bars indicate a range of ±1 SD.

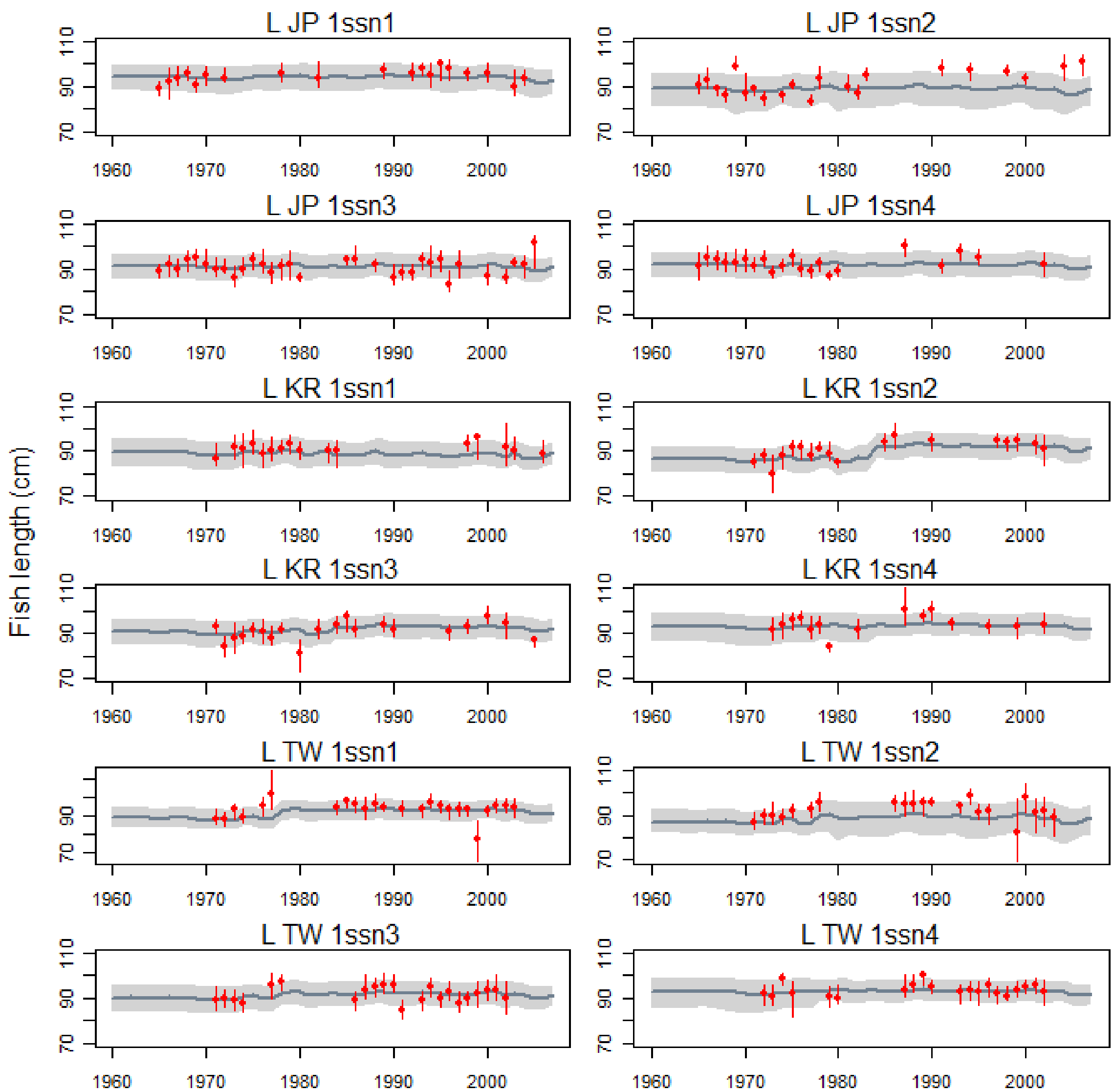


Figure 26a: A comparison of the observed (red points) and predicted (grey line) median fish length (FL, cm) of albacore tuna by fishery for the main fisheries with length data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated by year and only length samples with a minimum of 30 fish per year are plotted**.**

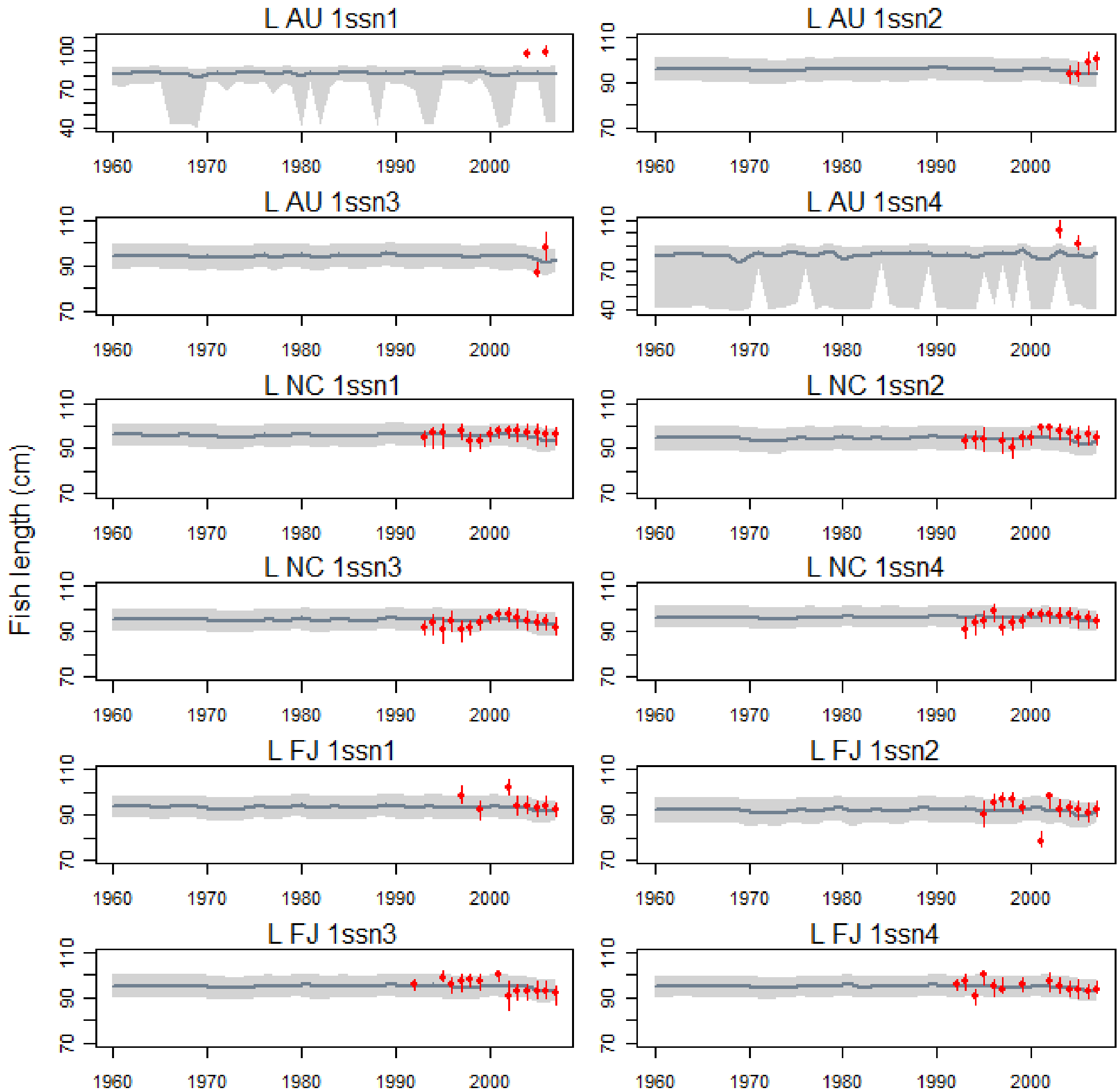


Figure 26b: A comparison of the observed (red points) and predicted (grey line) median fish length (FL, cm) of albacore tuna by fishery for the main fisheries with length data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated by year and only length samples with a minimum of 30 fish per year are plotted**.**

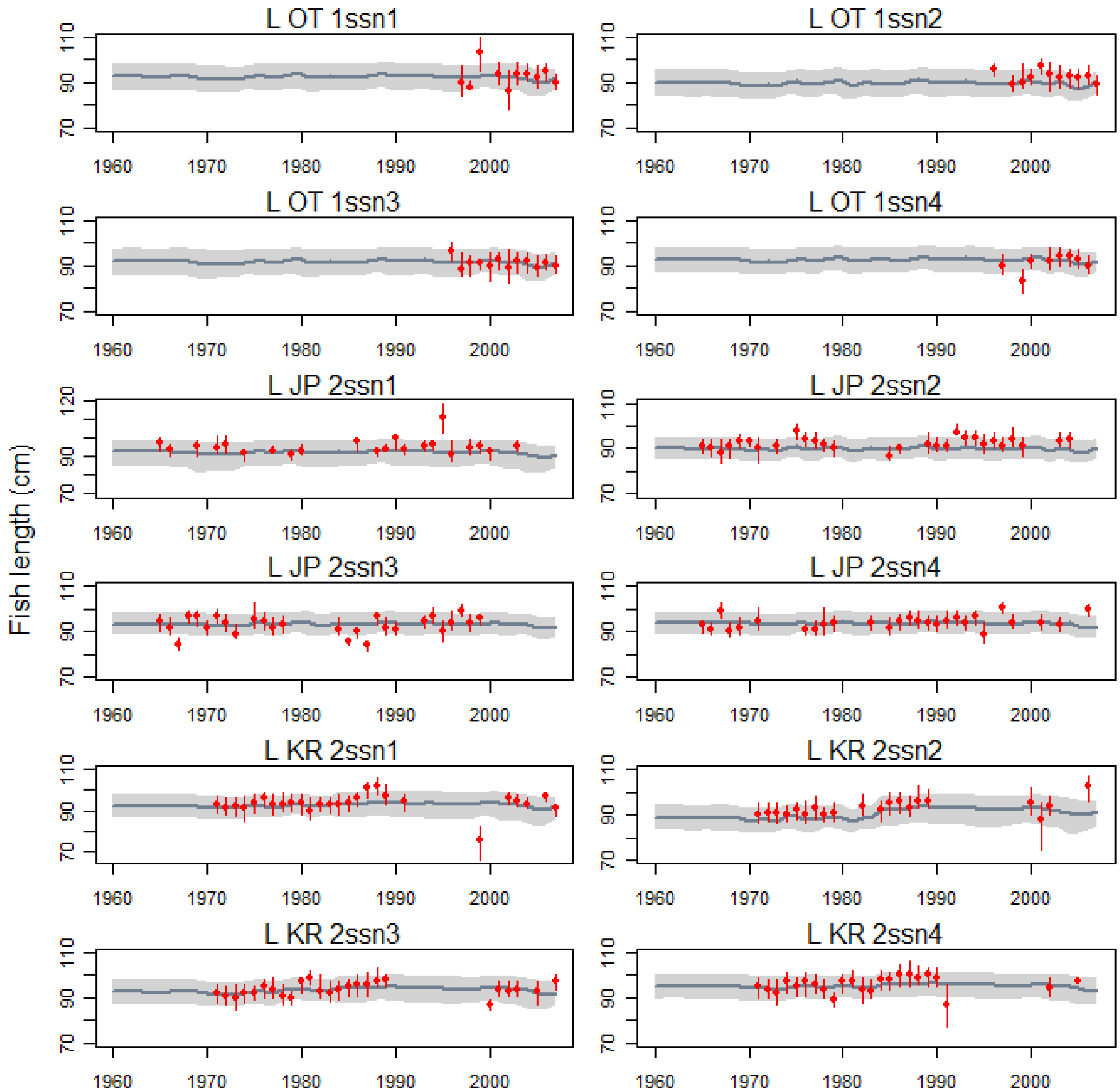


Figure 26c: A comparison of the observed (red points) and predicted (grey line) median fish length (FL, cm) of albacore tuna by fishery for the main fisheries with length data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated by year and only length samples with a minimum of 30 fish per year are plotted**.**

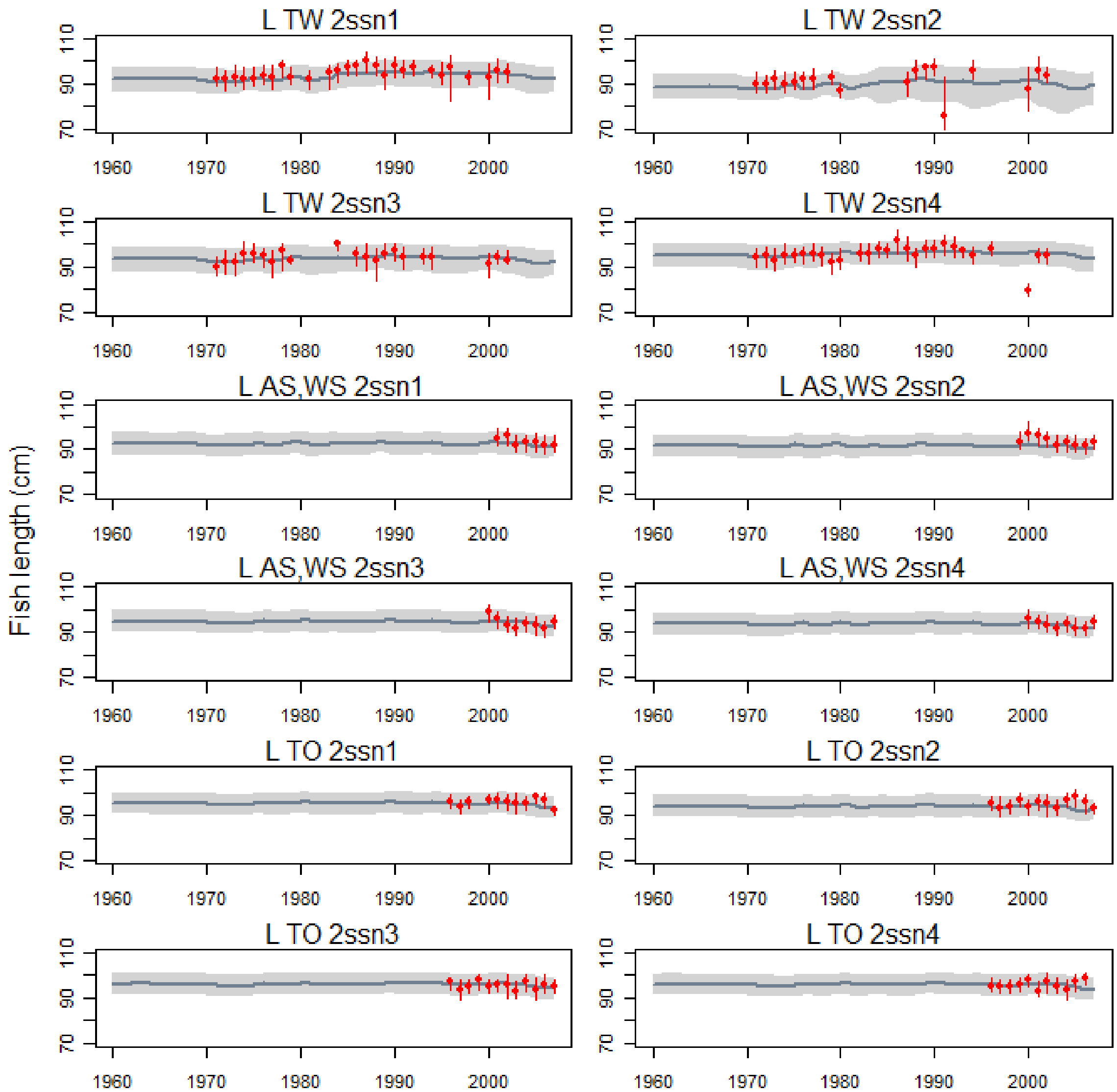


Figure 26d: A comparison of the observed (red points) and predicted (grey line) median fish length (FL, cm) of albacore tuna by fishery for the main fisheries with length data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated by year and only length samples with a minimum of 30 fish per year are plotted**.**

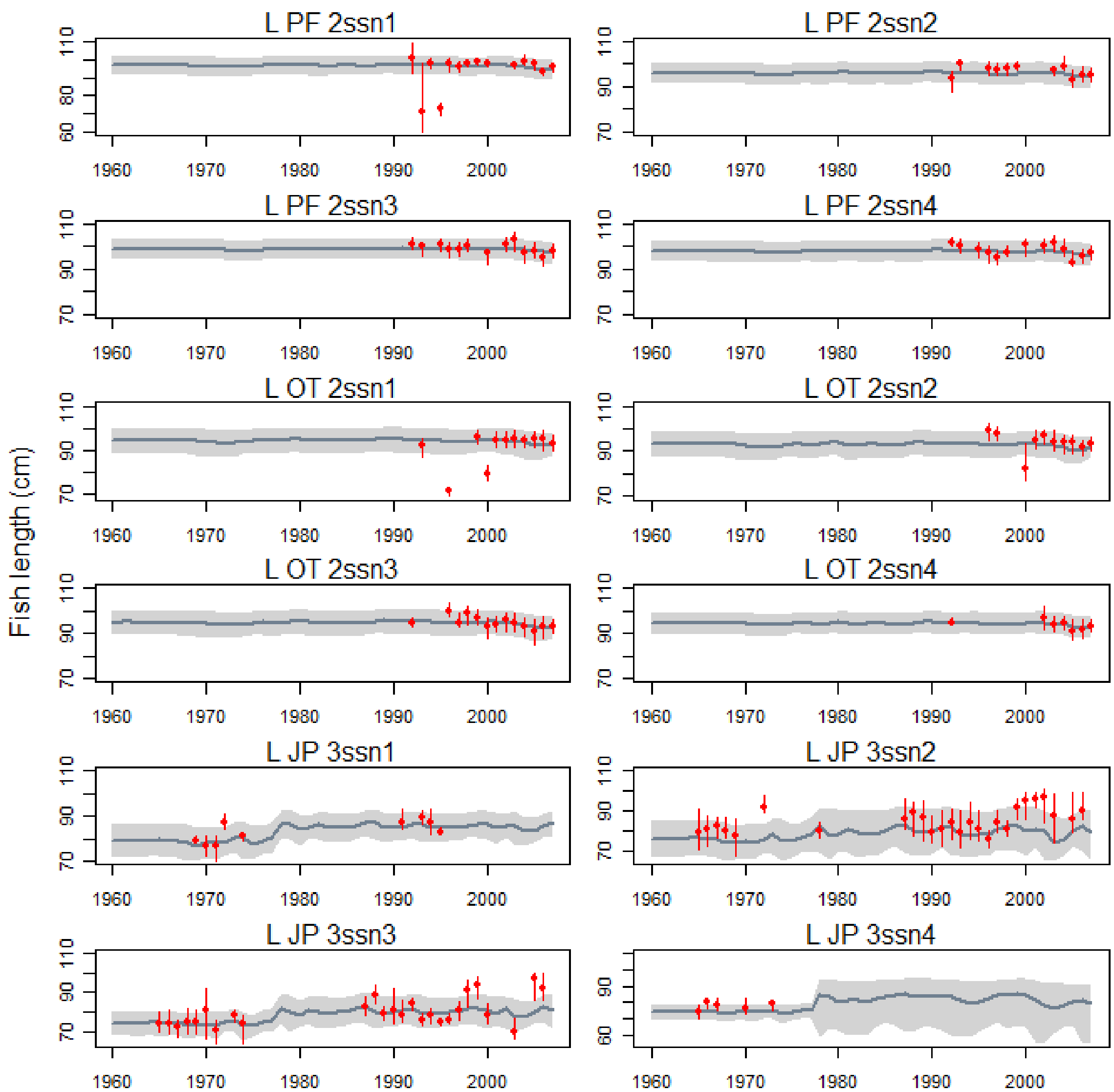


Figure 26e: A comparison of the observed (red points) and predicted (grey line) median fish length (FL, cm) of albacore tuna by fishery for the main fisheries with length data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated by year and only length samples with a minimum of 30 fish per year are plotted**.**

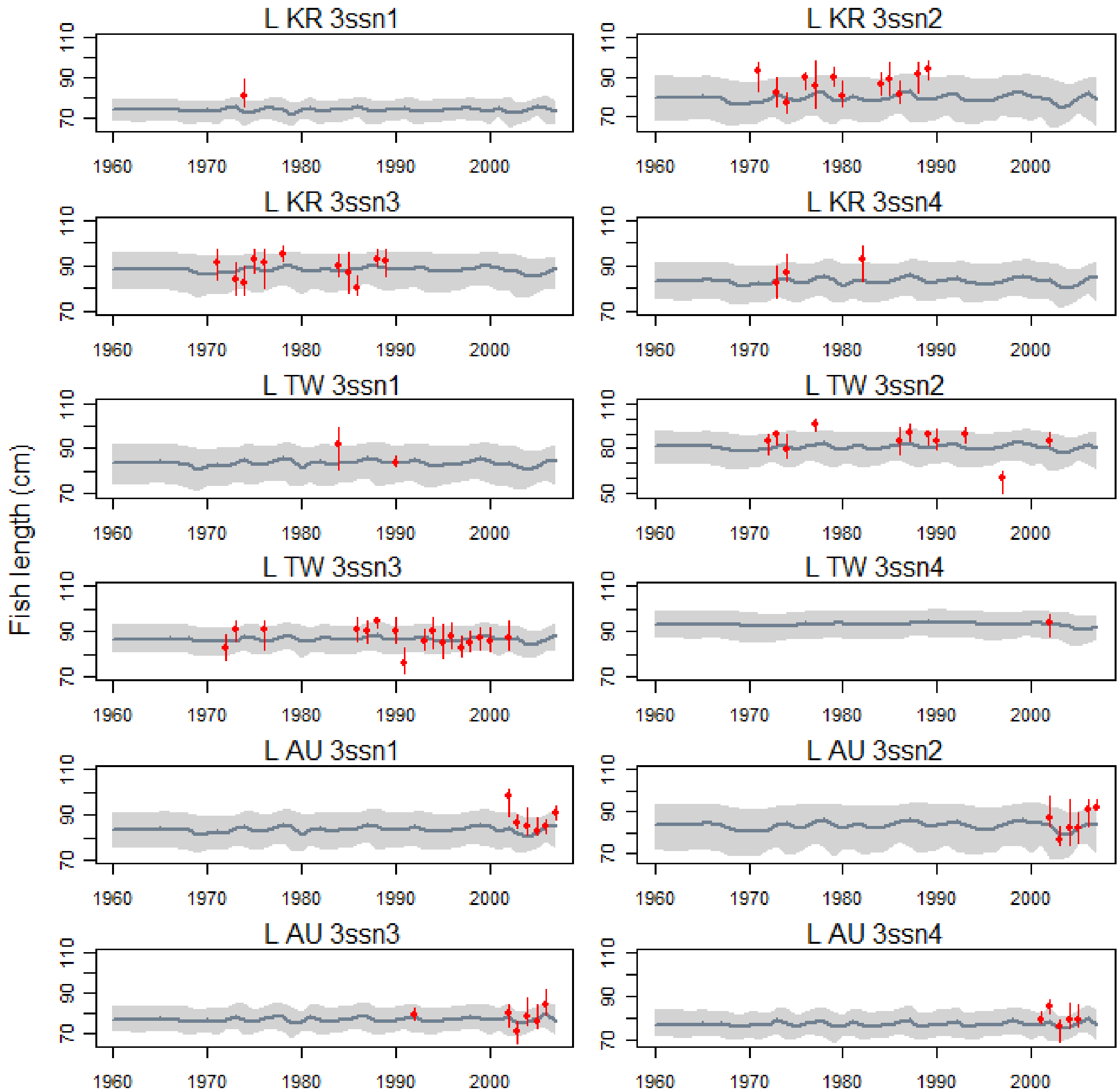


Figure 26f: A comparison of the observed (red points) and predicted (grey line) median fish length (FL, cm) of albacore tuna by fishery for the main fisheries with length data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated by year and only length samples with a minimum of 30 fish per year are plotted**.**

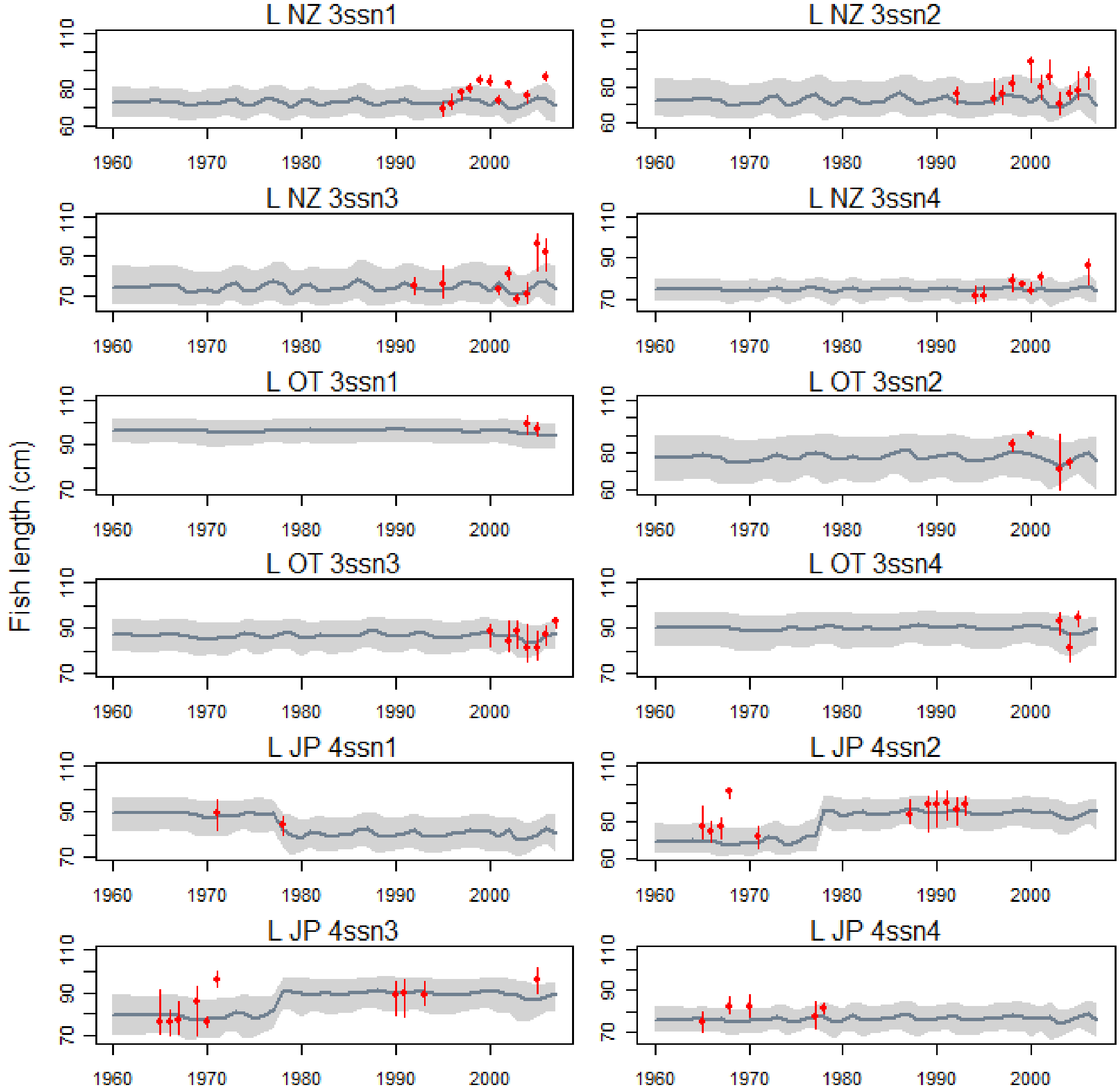


Figure 26g: A comparison of the observed (red points) and predicted (grey line) median fish length (FL, cm) of albacore tuna by fishery for the main fisheries with length data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated by year and only length samples with a minimum of 30 fish per year are plotted.

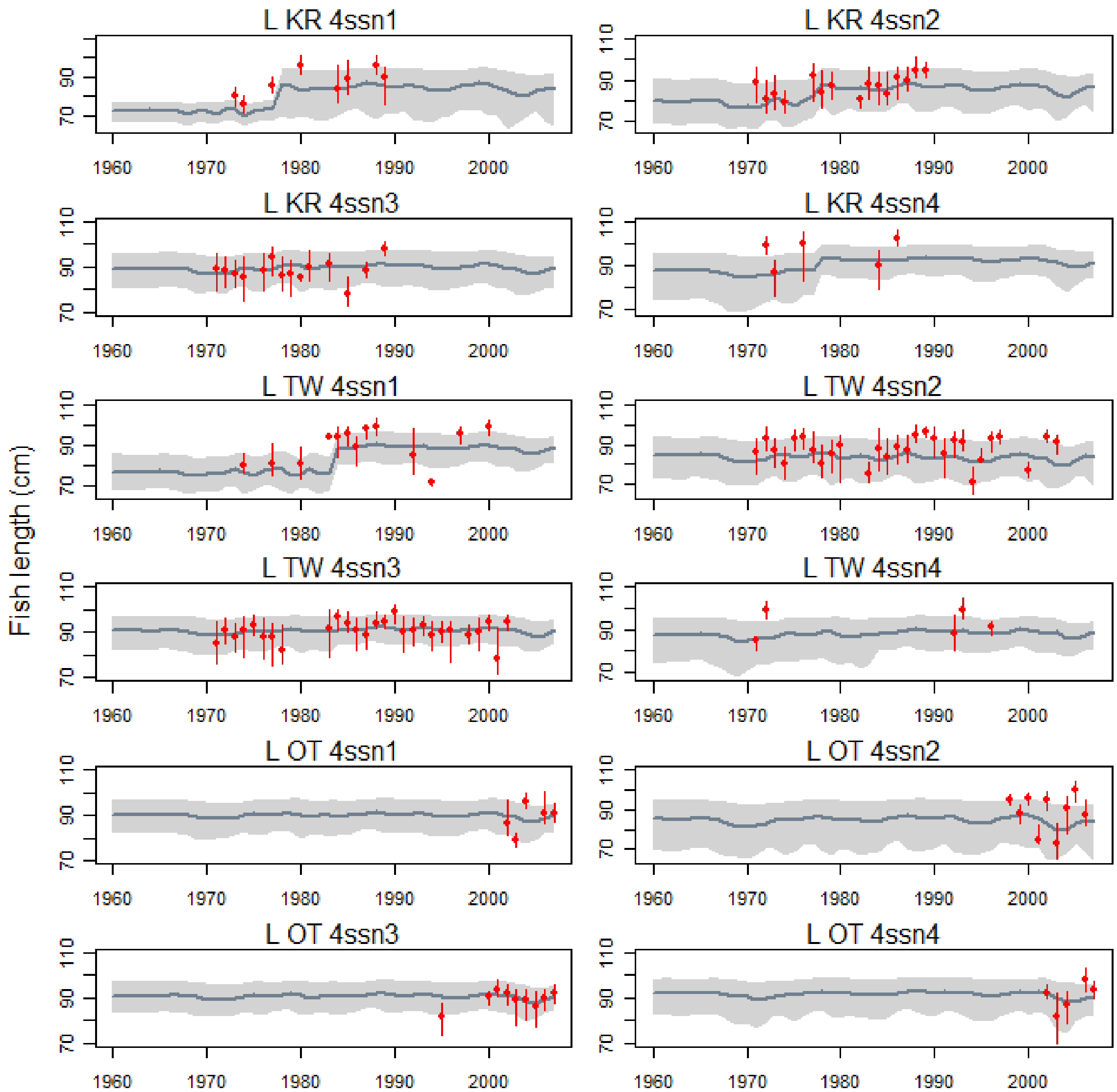


Figure 26h: A comparison of the observed (red points) and predicted (grey line) median fish length (FL, cm) of albacore tuna by fishery for the main fisheries with length data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated by year and only length samples with a minimum of 30 fish per year are plotted**.**

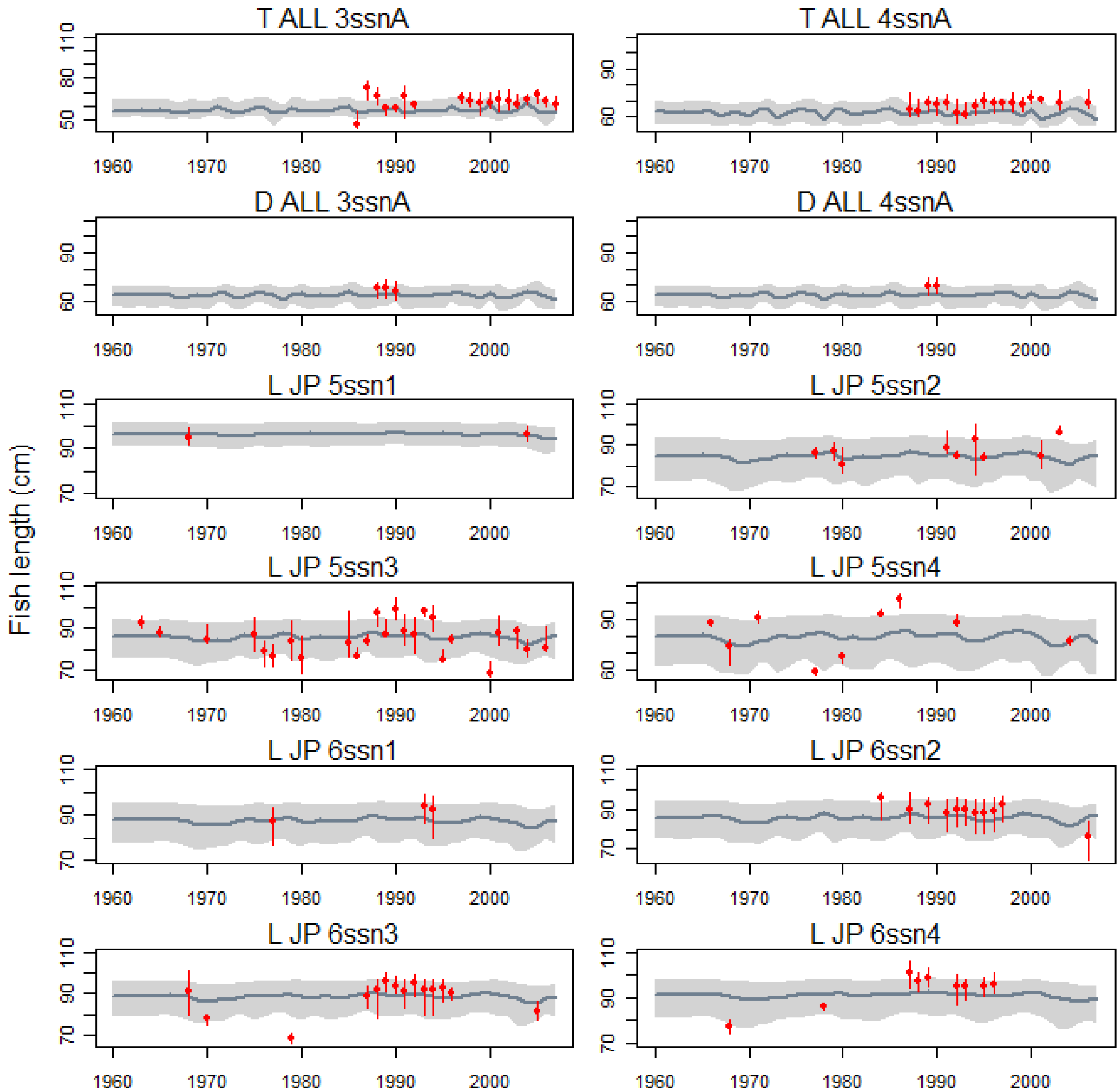


Figure 26i: A comparison of the observed (red points) and predicted (grey line) median fish length (FL, cm) of albacore tuna by fishery for the main fisheries with length data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated by year and only length samples with a minimum of 30 fish per year are plotted**.**

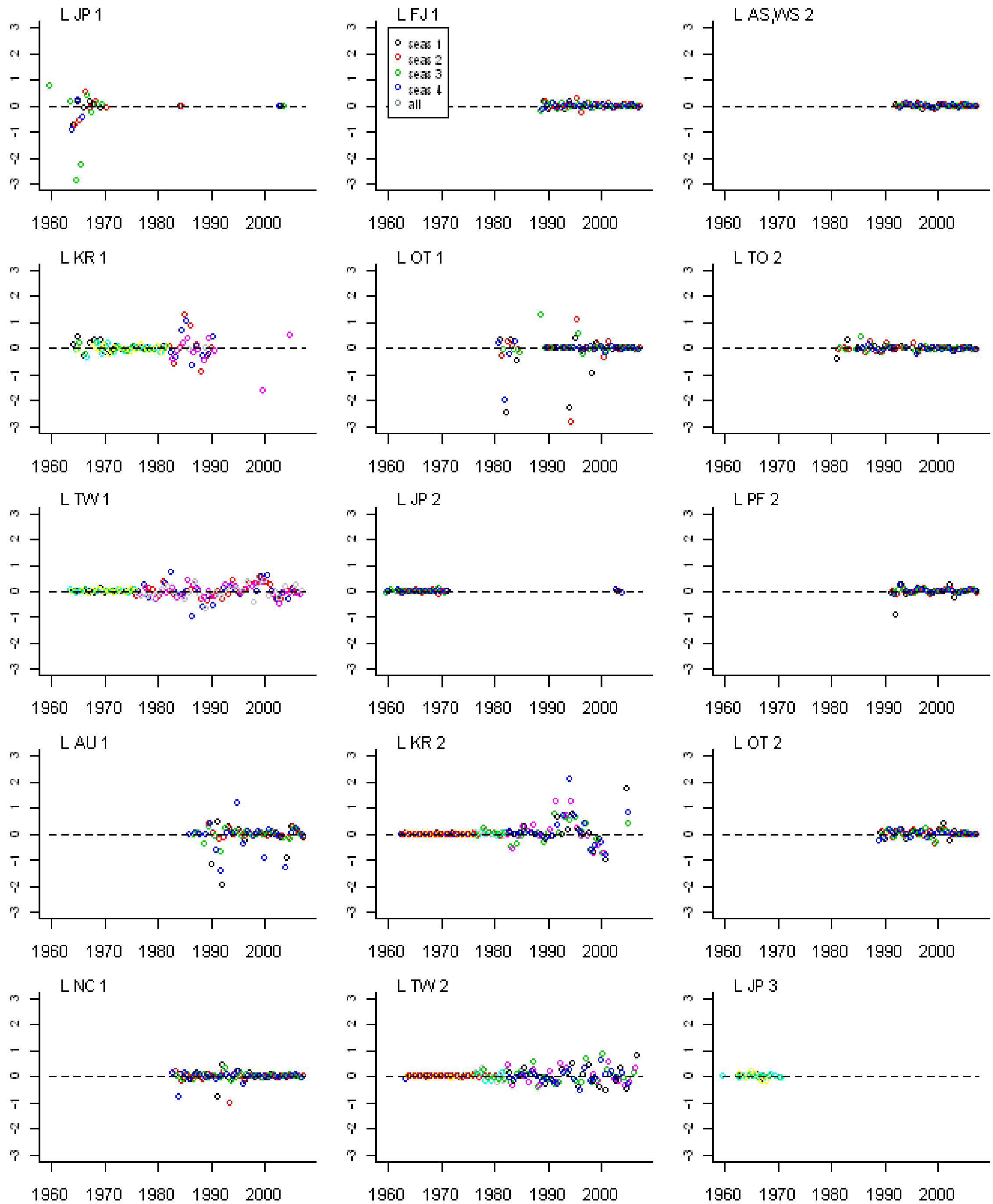


Figure 27a: Quarterly effort deviates by fishery.

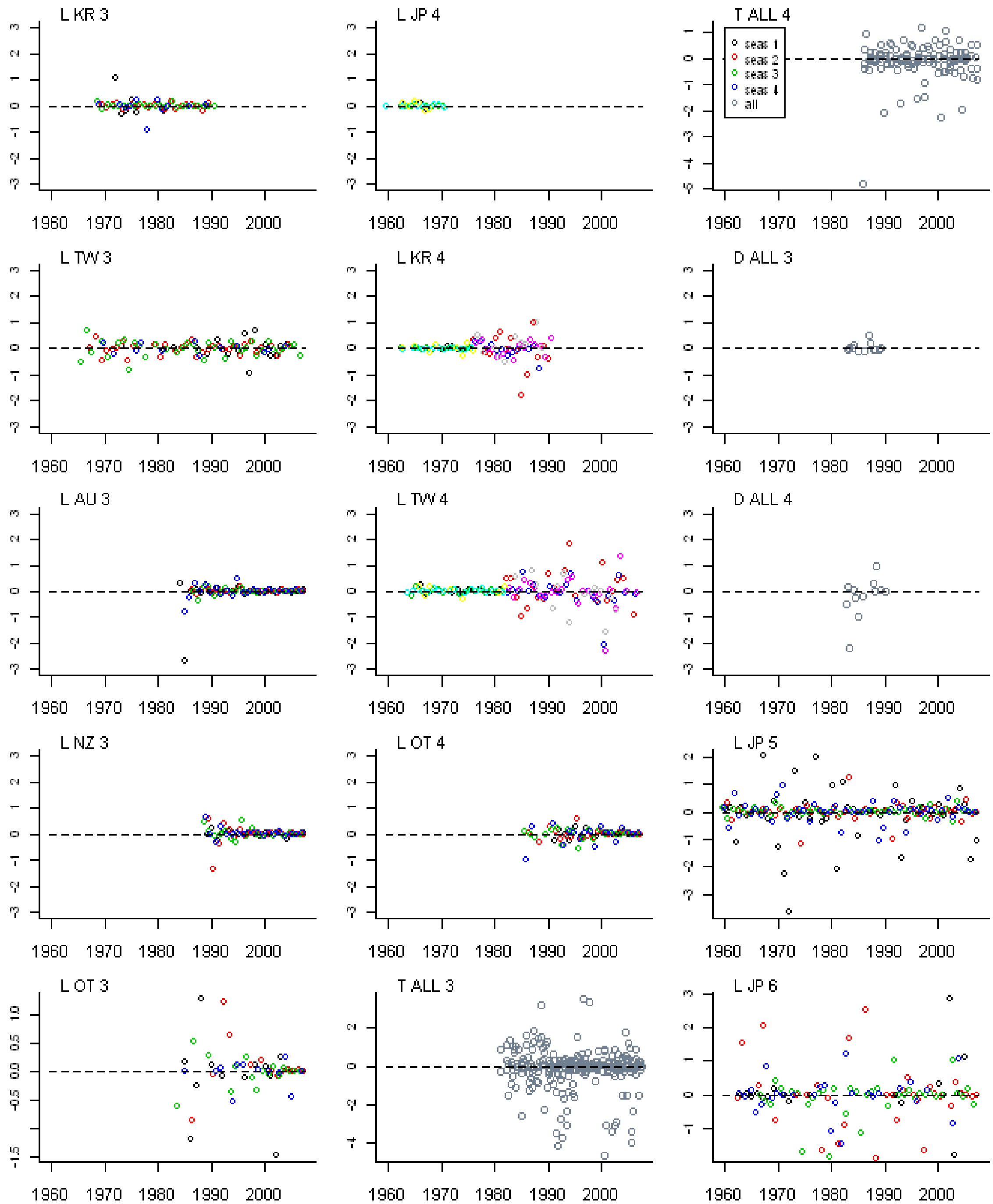


Figure 27b: Quarterly effort deviates by fishery.

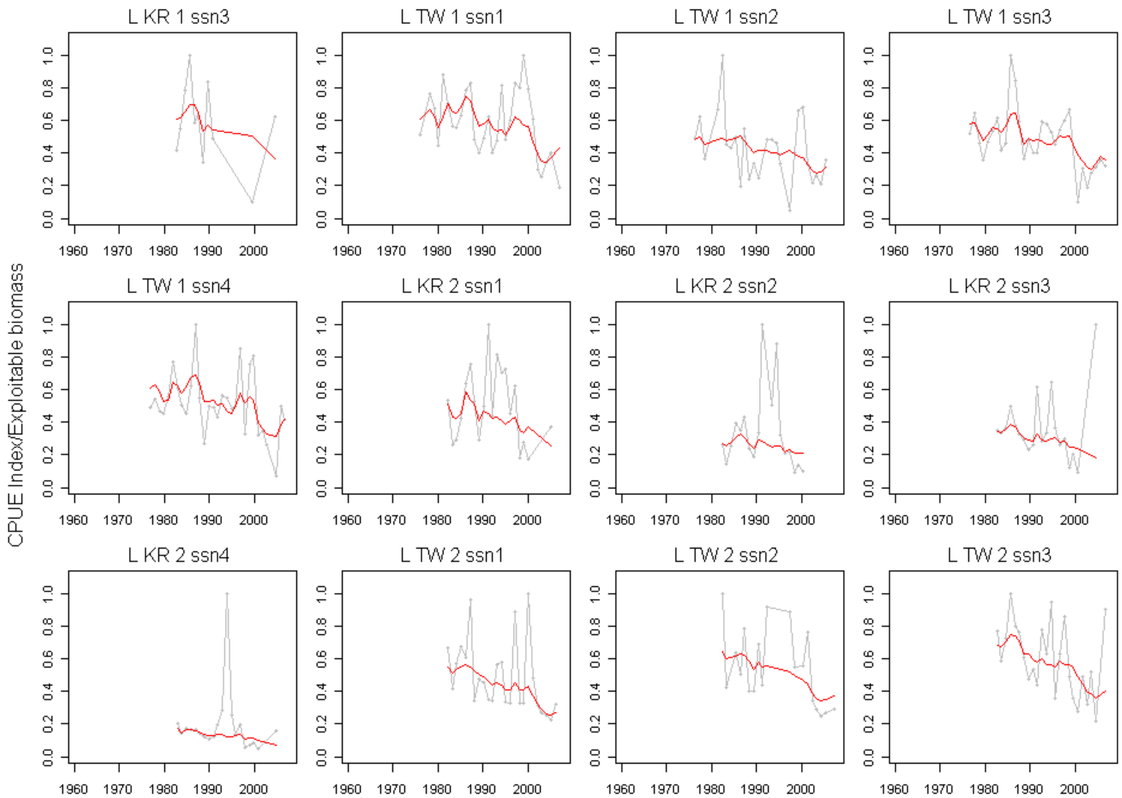


Figure 28a: A comparison of the observed catch rate (number of fish) (grey points and line) and the predicted exploitable biomass from the quarterly observations of catch and effort from each of the standardised fisheries (red line).

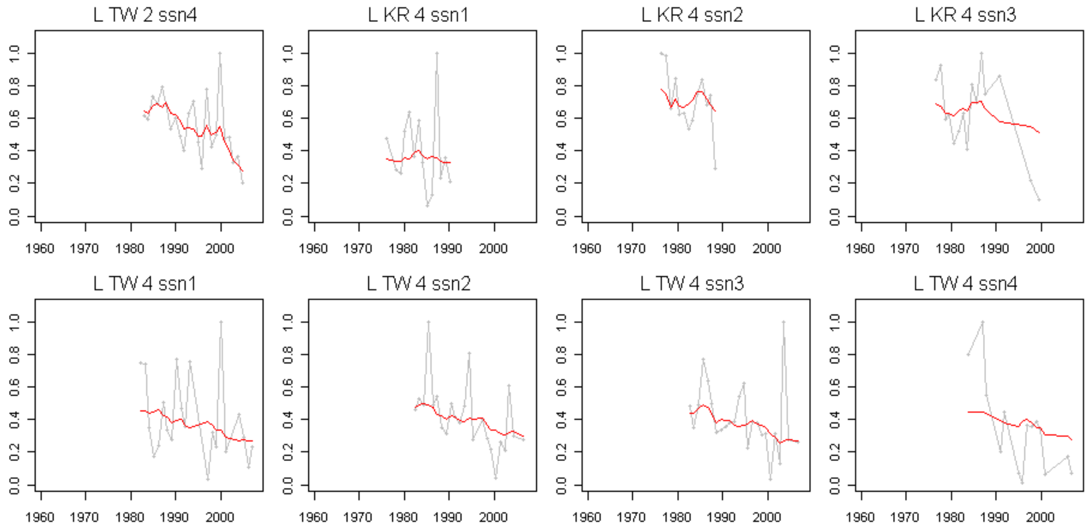


Figure 28b: A comparison of the observed catch rate (number of fish) (grey points and line) and the predicted exploitable biomass from the quarterly observations of catch and effort from each of the standardised fisheries (red line).

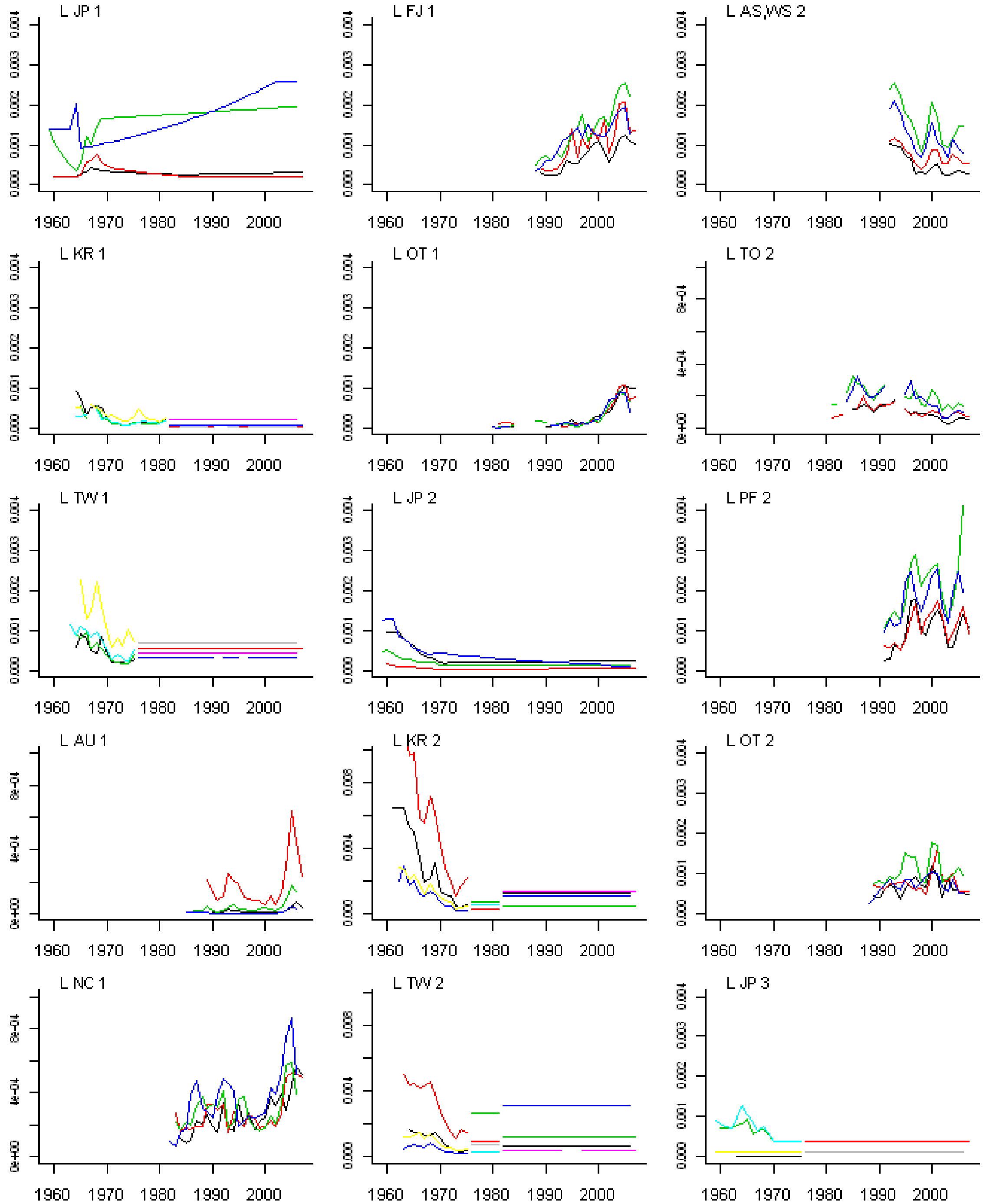


Figure 29a: Annualised trends in catchability by fishery.

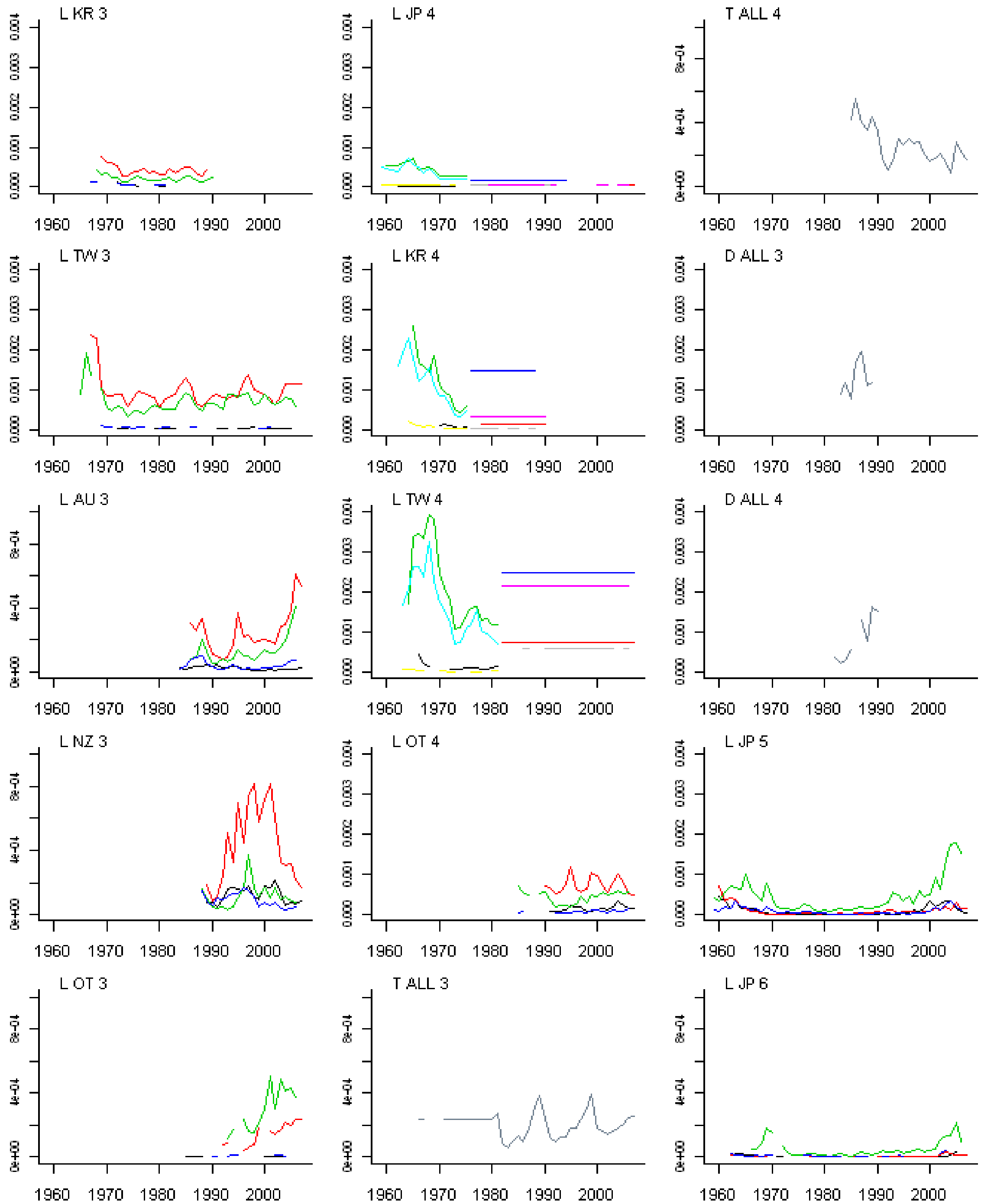


Figure 29b: Annualised trends in catchability by fishery

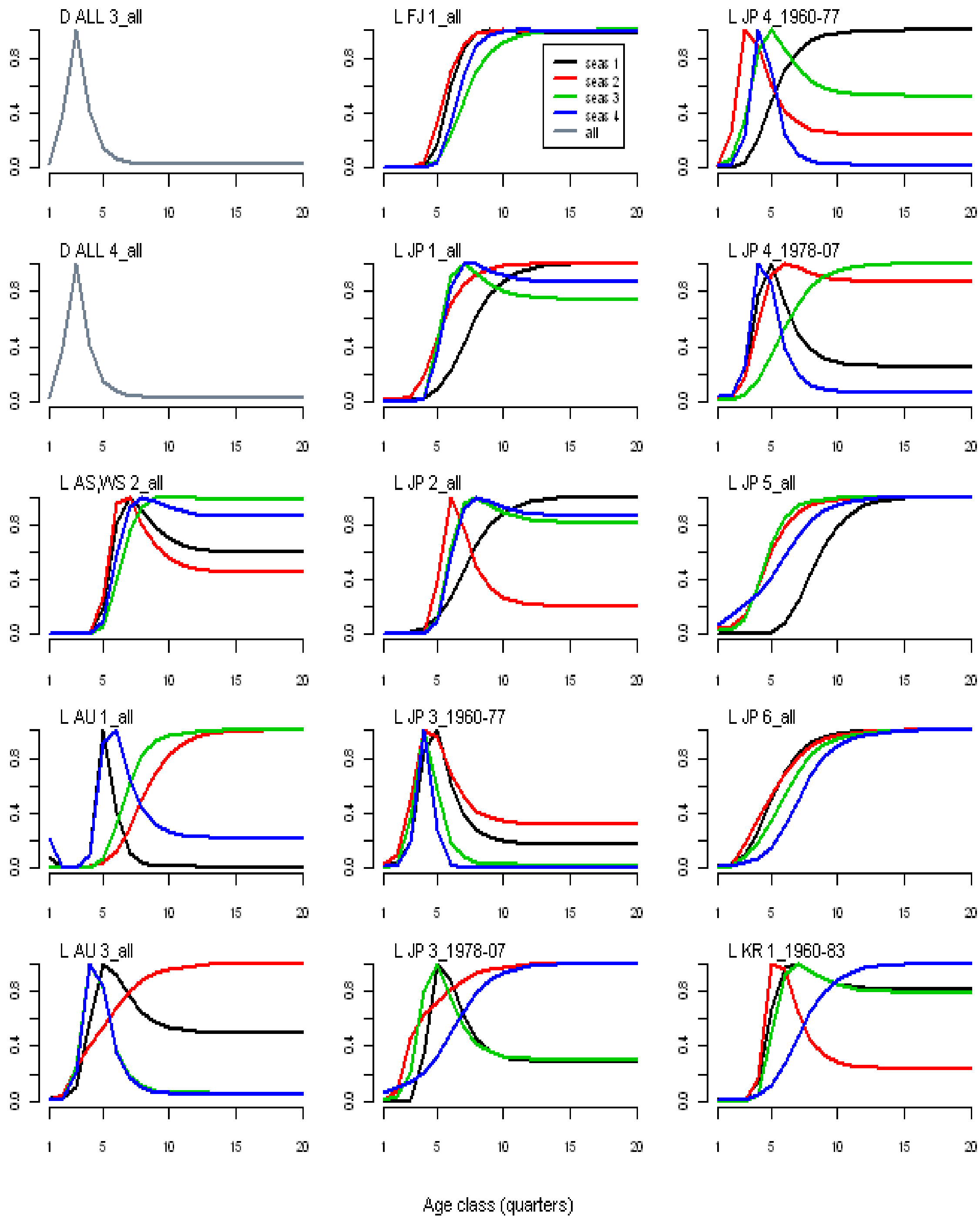


Figure 30a: Selectivity at age (years) by fishery.

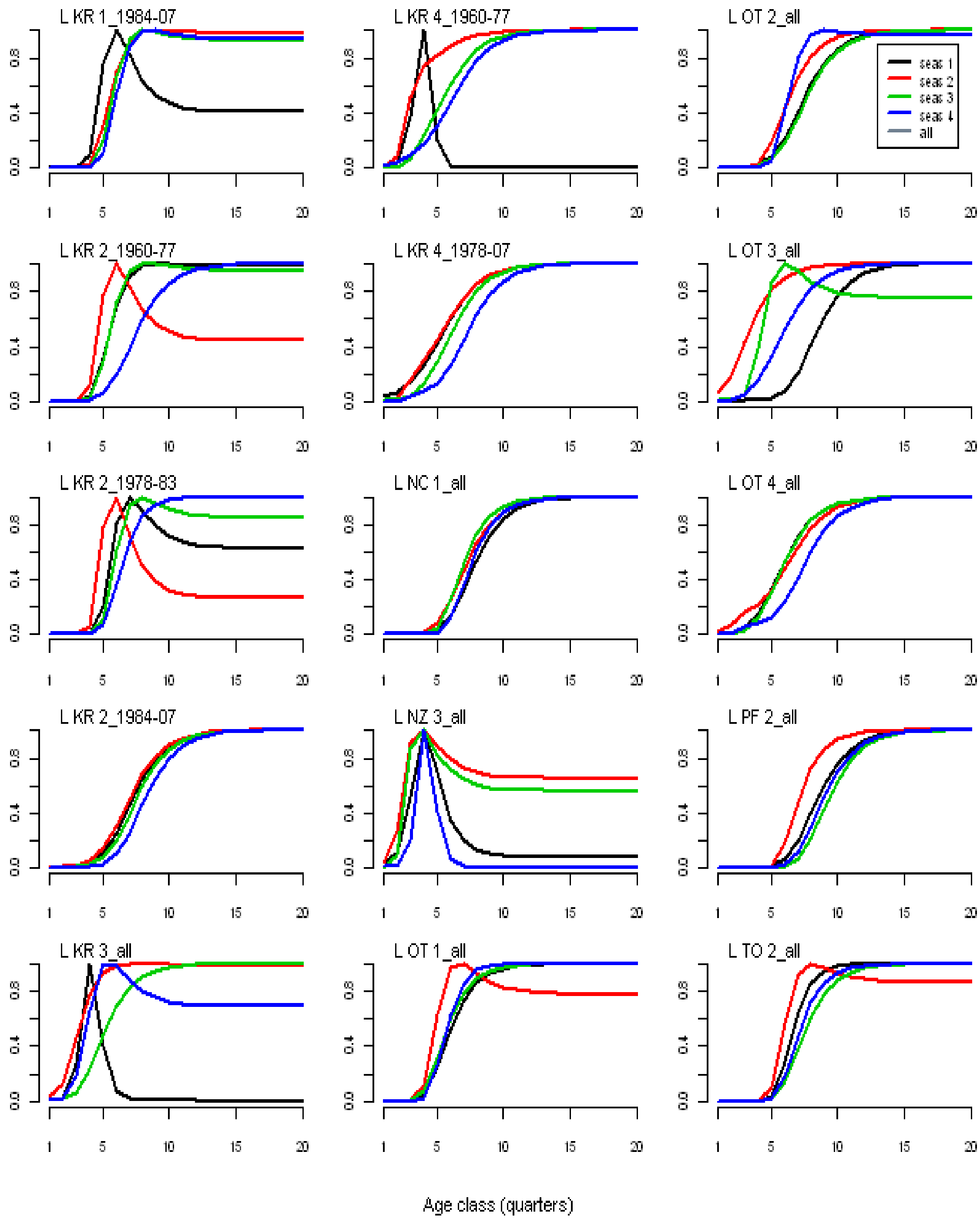


Figure 30b: Selectivity at age (years) by fishery.

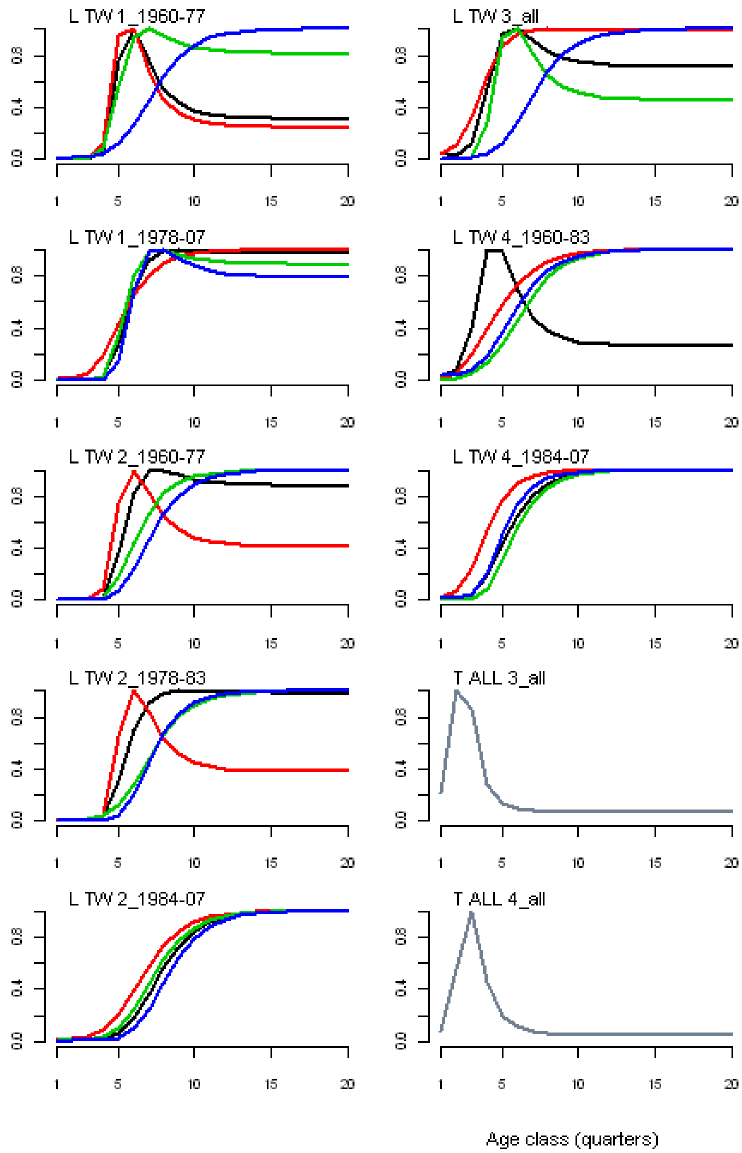


Figure 30c: Selectivity at age (years) by fishery.

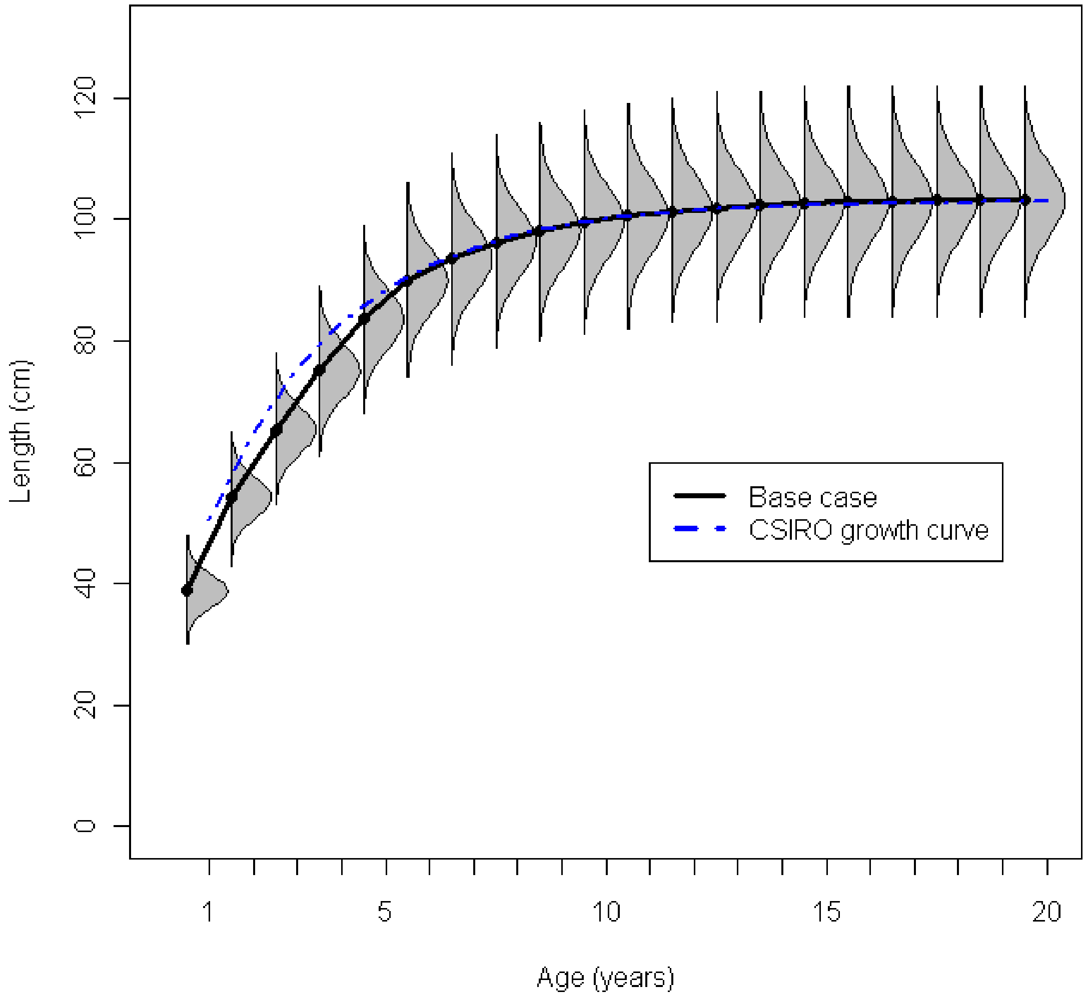


Figure 31: Estimated length (fork length) at age (years) (solid line) and the 95% confidence interval. The dashed line represents initial values included in the model from the von Bertalanffy parameters.

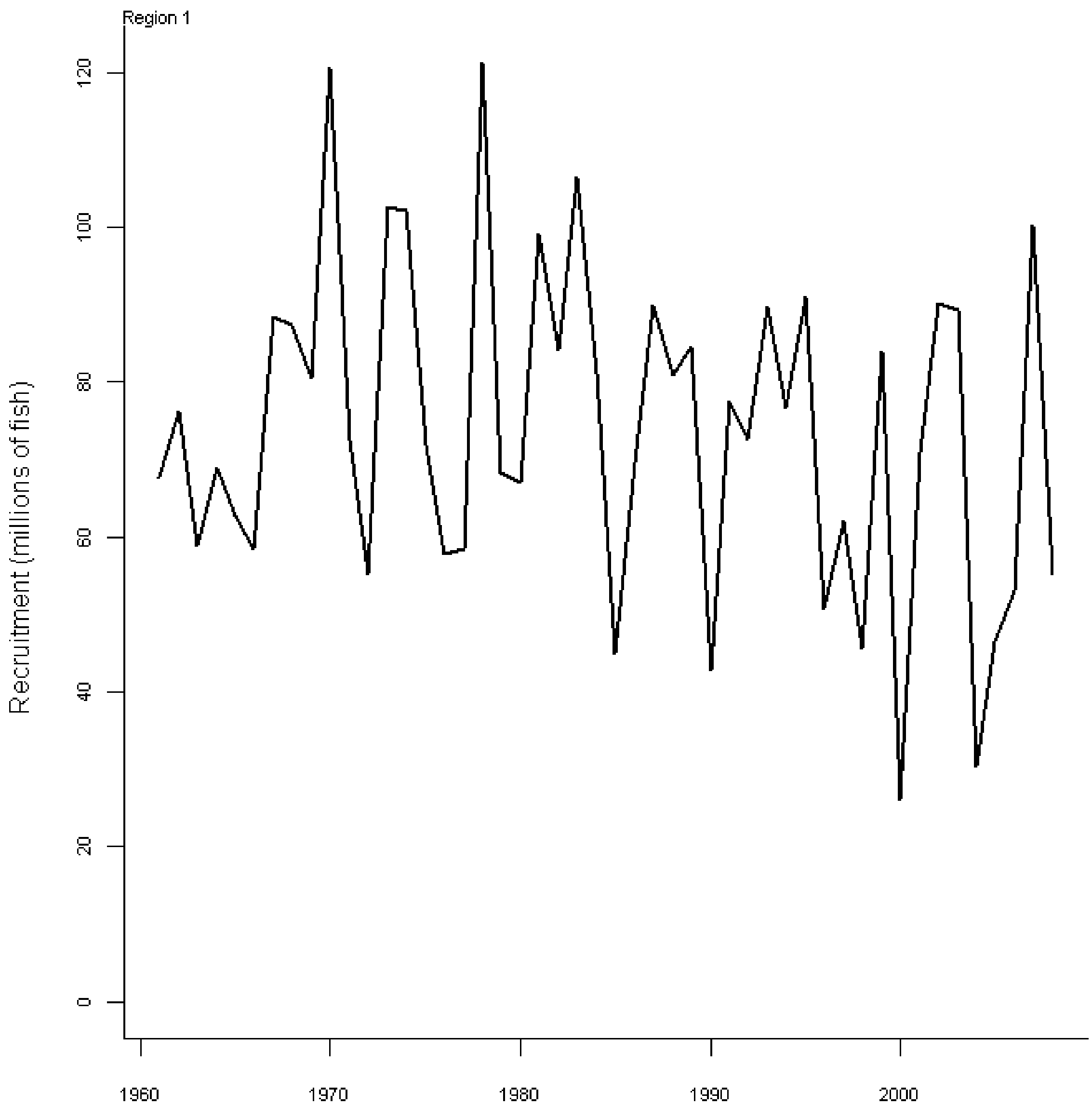


Figure 32: Annual recruitment (number of fish) estimates.

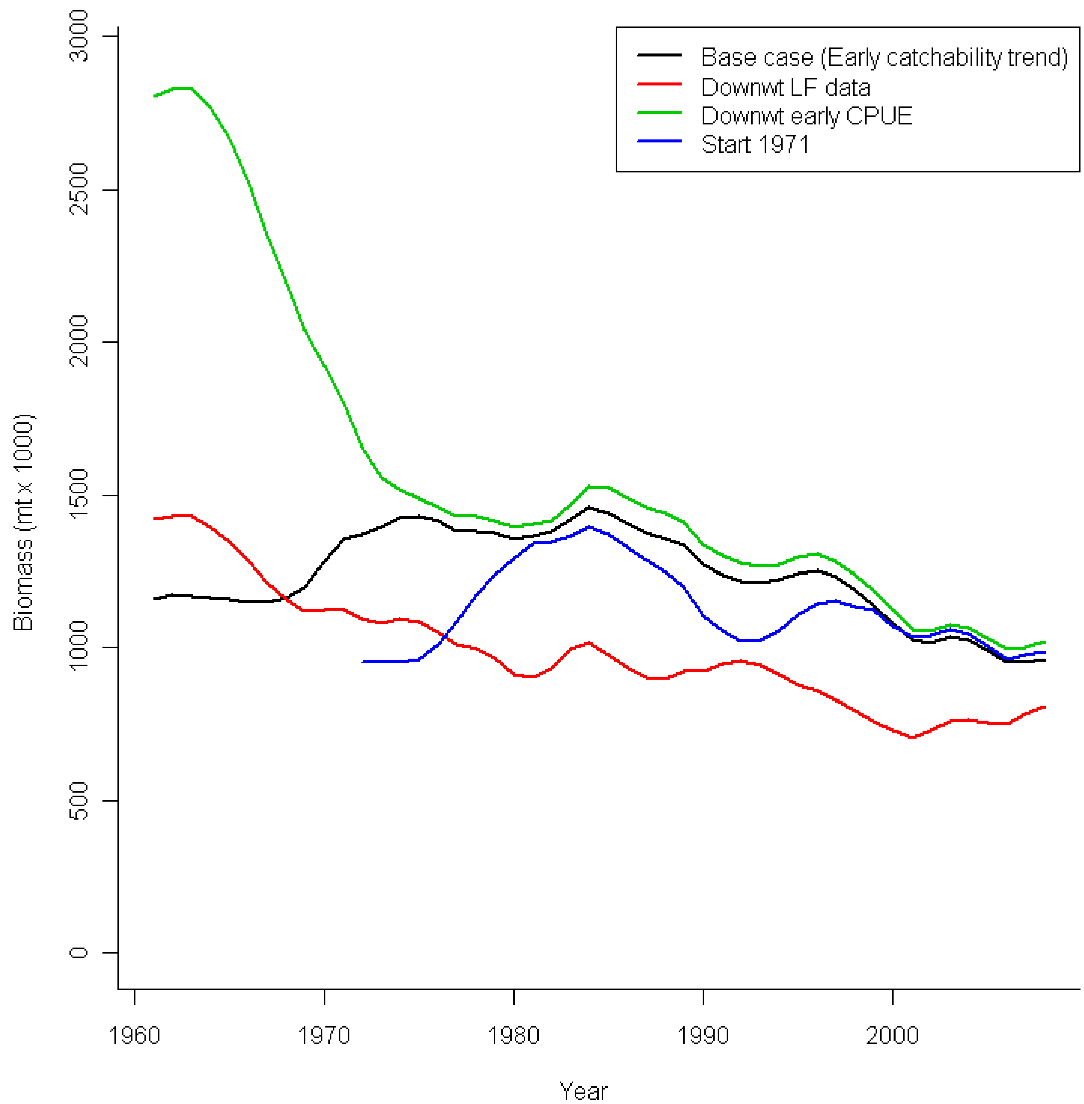


Figure 33: Annual estimates of total biomass (thousands of metric tonnes). Several scenarios are shown to illustrate that a) early biomass is particularly uncertain, and b) the recent biomass trend is better established than the absolute level.

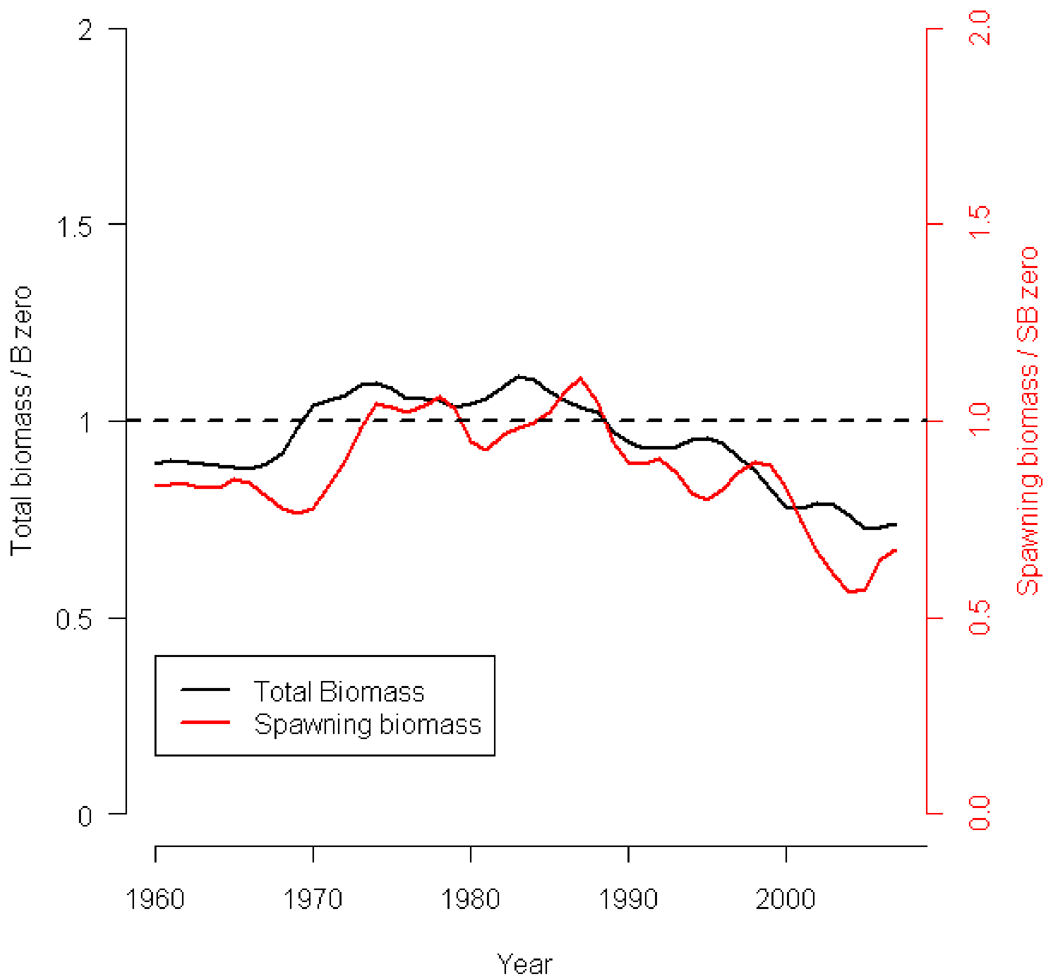


Figure 34: Time series of the ratios *B / B_0 and SB / SB_0*. Initial biomasses are estimated to be well above equilibrium unfished levels (represented by *B_0 and SB_0*).

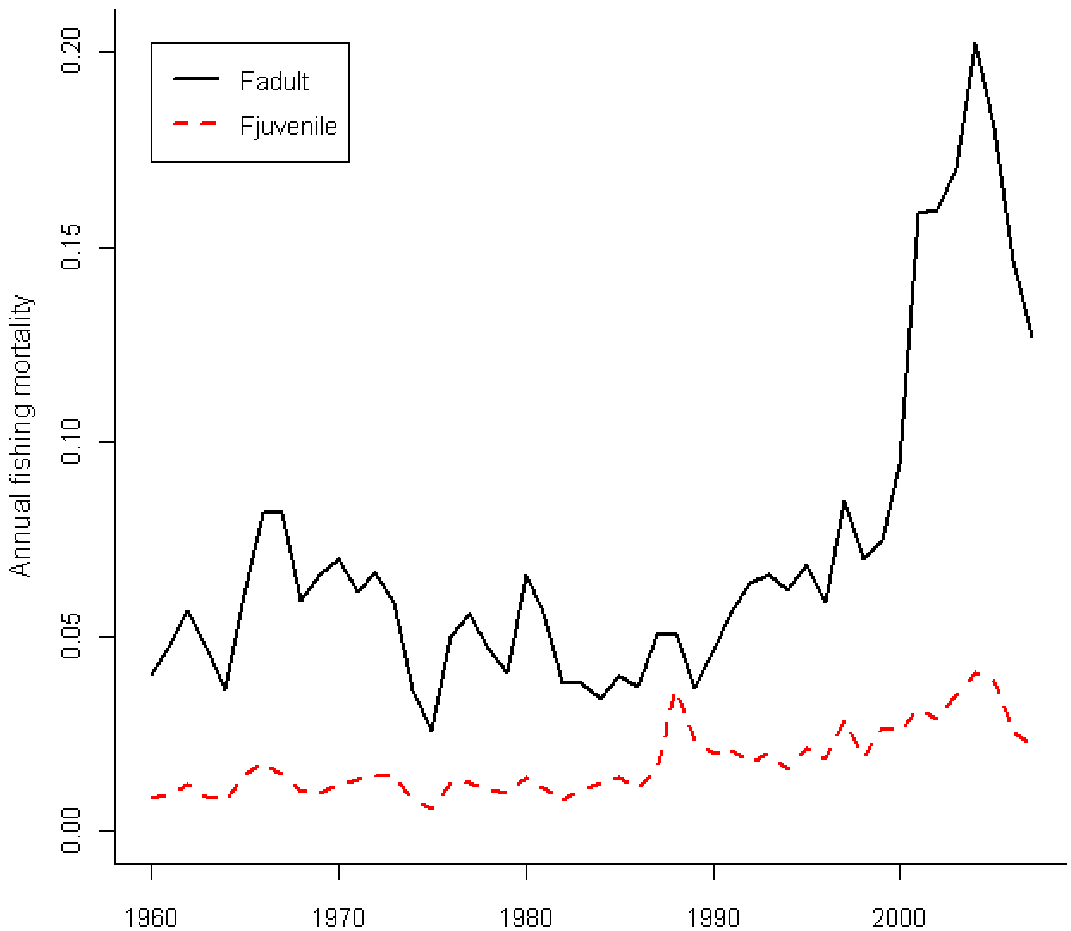


Figure 35: Annual estimates of fishing mortality for juvenile and adult South Pacific albacore.

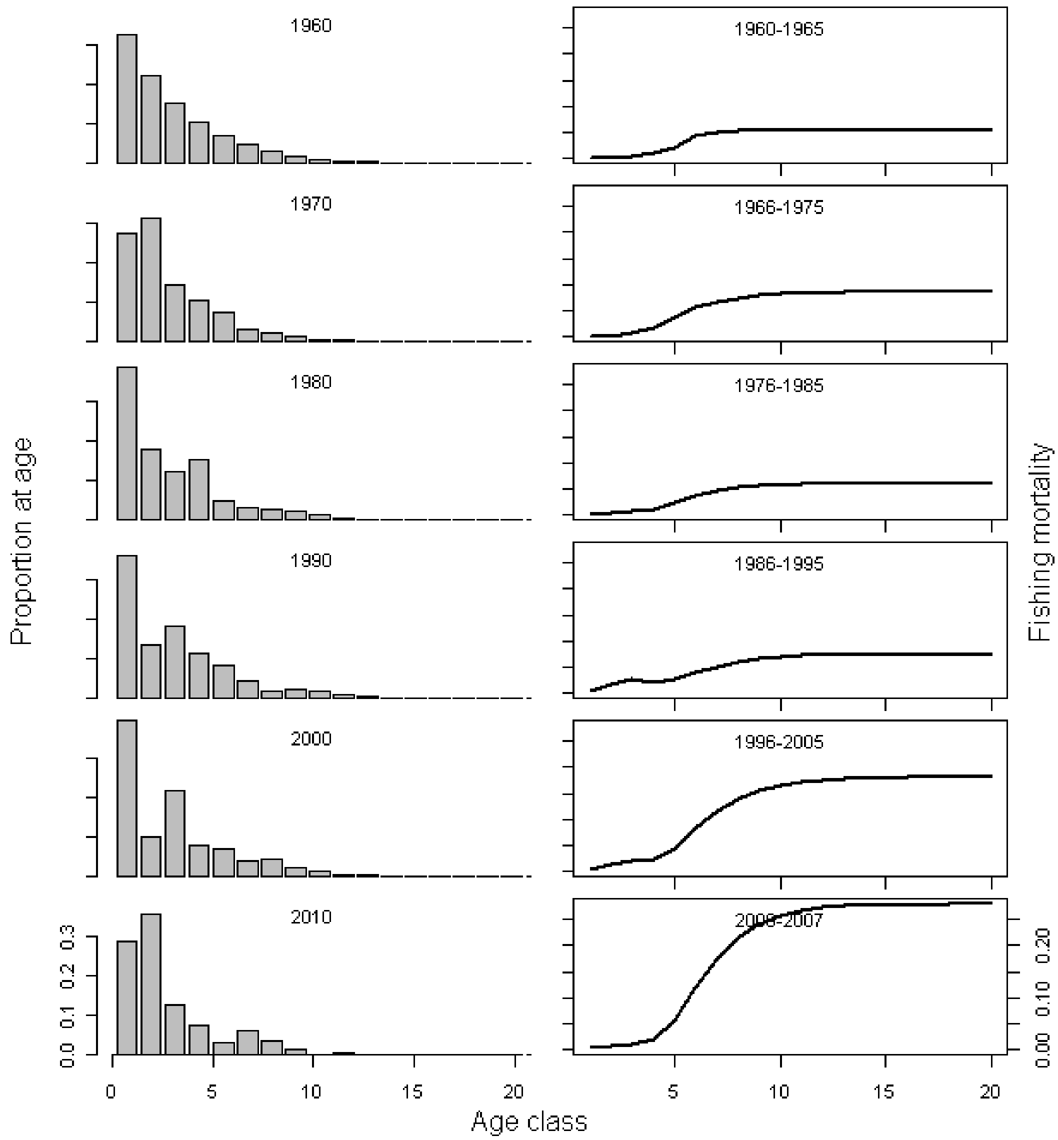


Figure 36: Estimated proportion at age (left) and mortality at age (right) by year at decadal intervals, and for 2006.

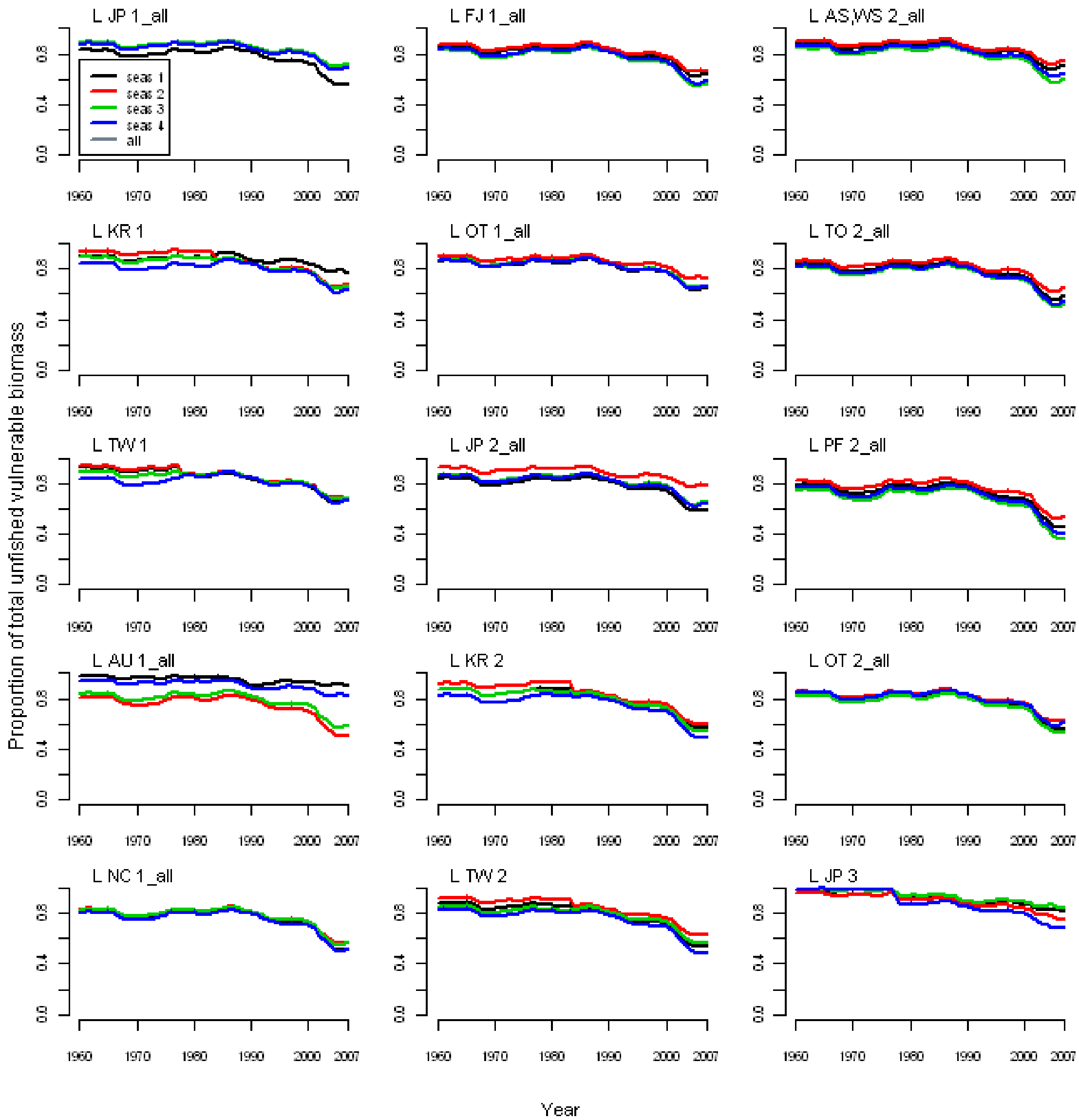
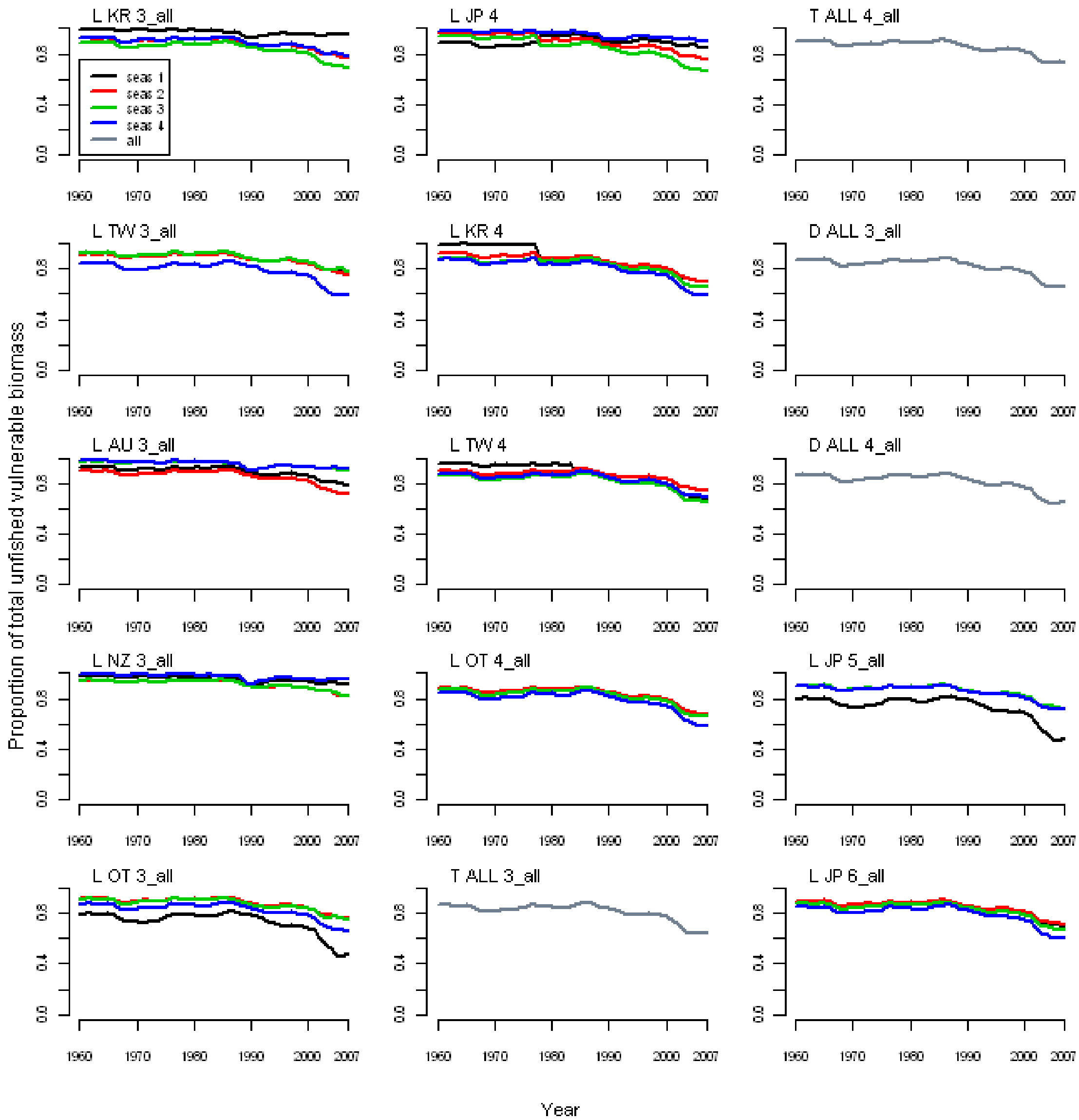


Figure 37a: The ratio between the level of exploitable biomass for individual fisheries and the level of exploitable biomass predicted in the absence of fishing.


L KR 3_all
L JP 4
T ALL 4_all
L TW 3_all
L KR 4
D ALL 3_all
L AU 3_all
L TW 4
D ALL 4_all
L NZ 3_all
L OT 4_all
L JP 5_all
L OT 3_all
T ALL 3_all
L JP 6_all
seas 1
seas 2
seas 3
seas 4
all
Proportion of total unfished vulnerable biomass
Year
0.0
0.4
0.8
1960
1970
1980
1990
2000
2007

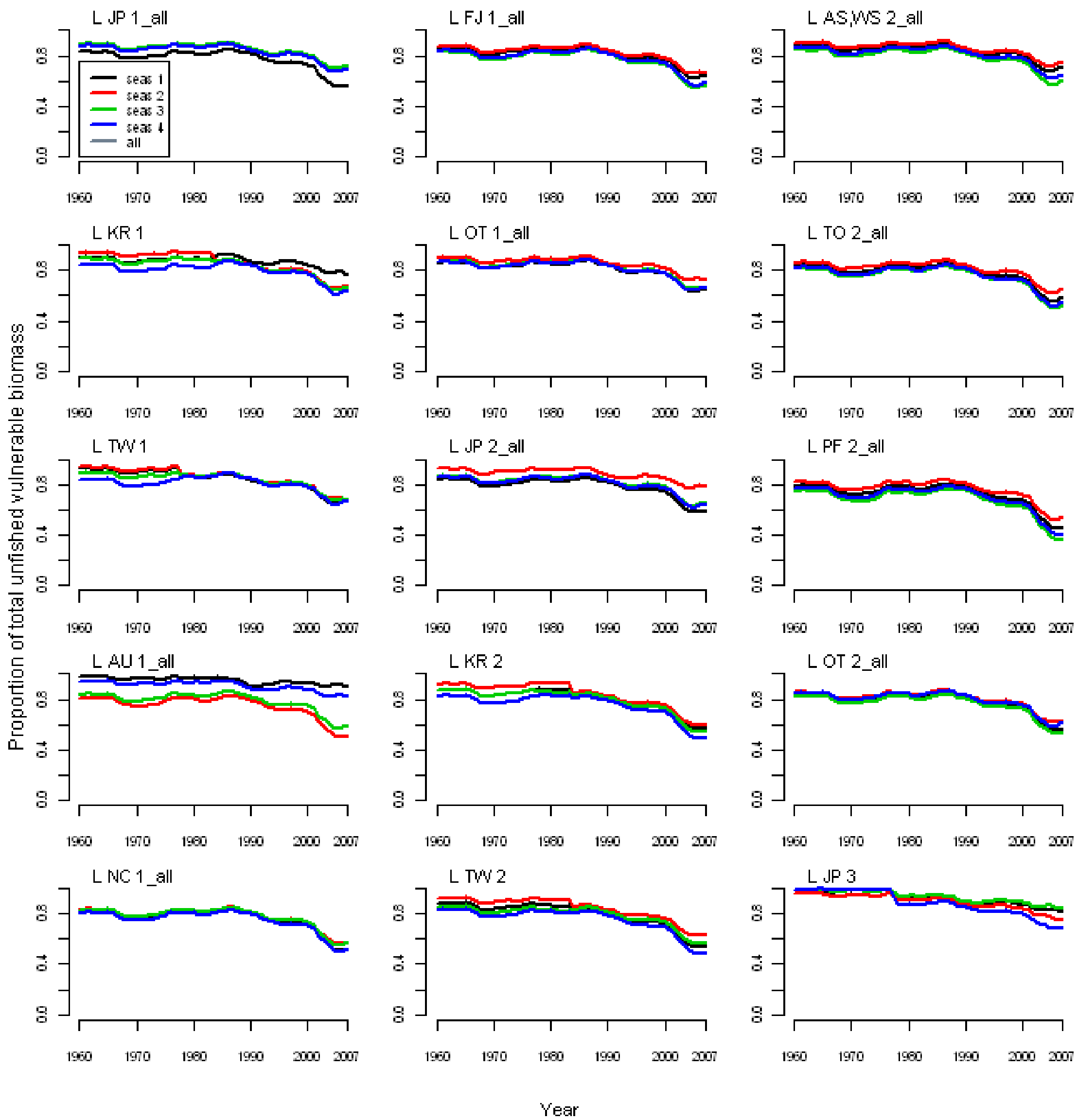


Figure 37b. The ratio between the level of exploitable biomass for individual fisheries and the level of exploitable biomass predicted in the absence of fishing.

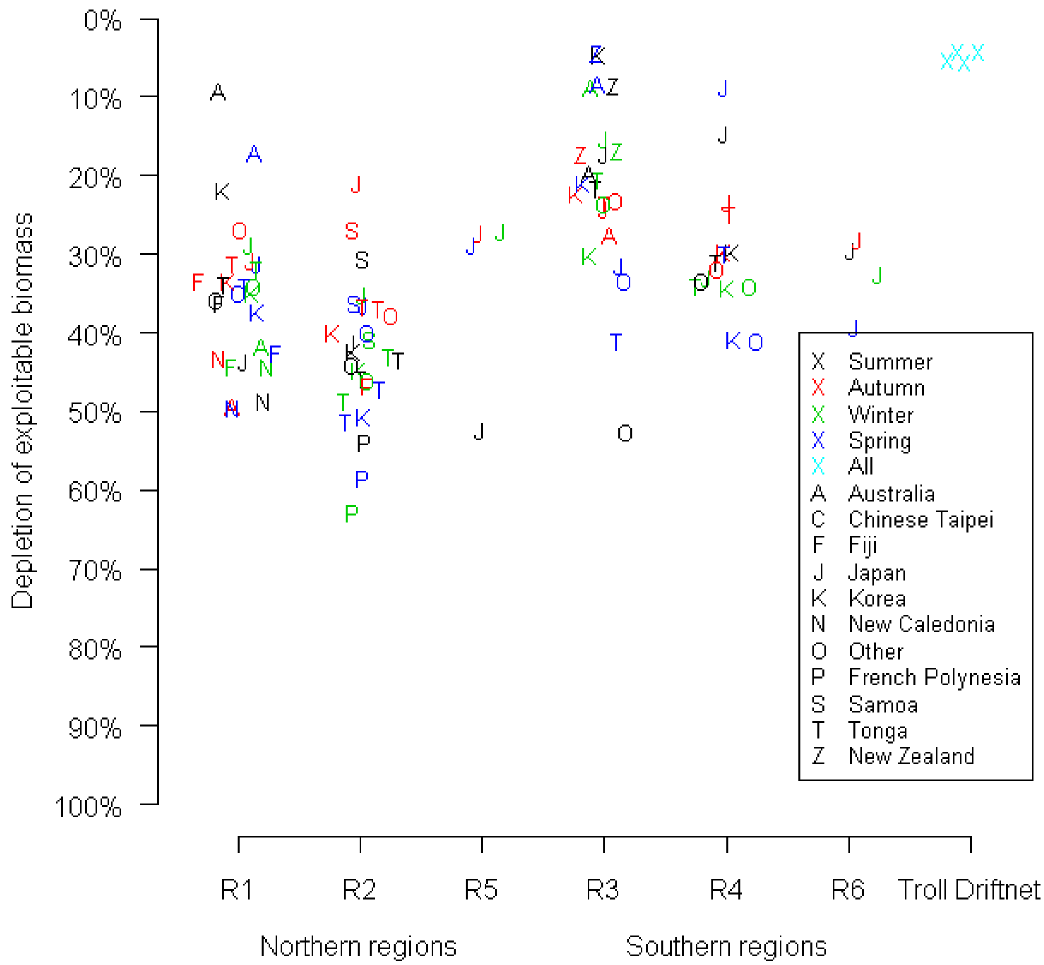


Figure 38: Average depletion (due to all fishing) of exploitable biomass by fishery for the period 2004–2006, by fishery. Fisheries are coloured by season, and labelled according to fishing nation. The four light blue crosses represent the troll and driftnet fisheries.

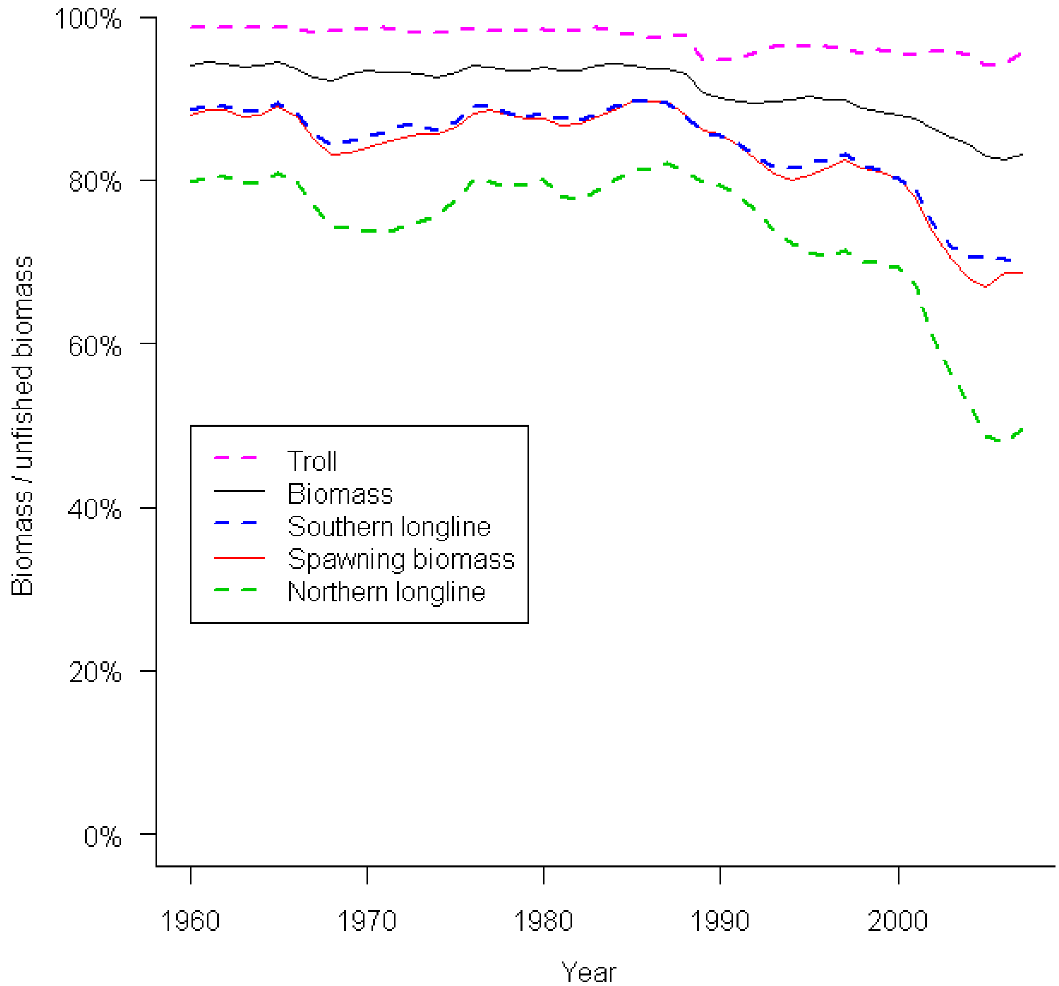


Figure 39: Decline in biomass due to the impact of fishing mortality, for exploitable biomass in the troll, southern longline, and northern longline fisheries, for total biomass and for spawning biomass.

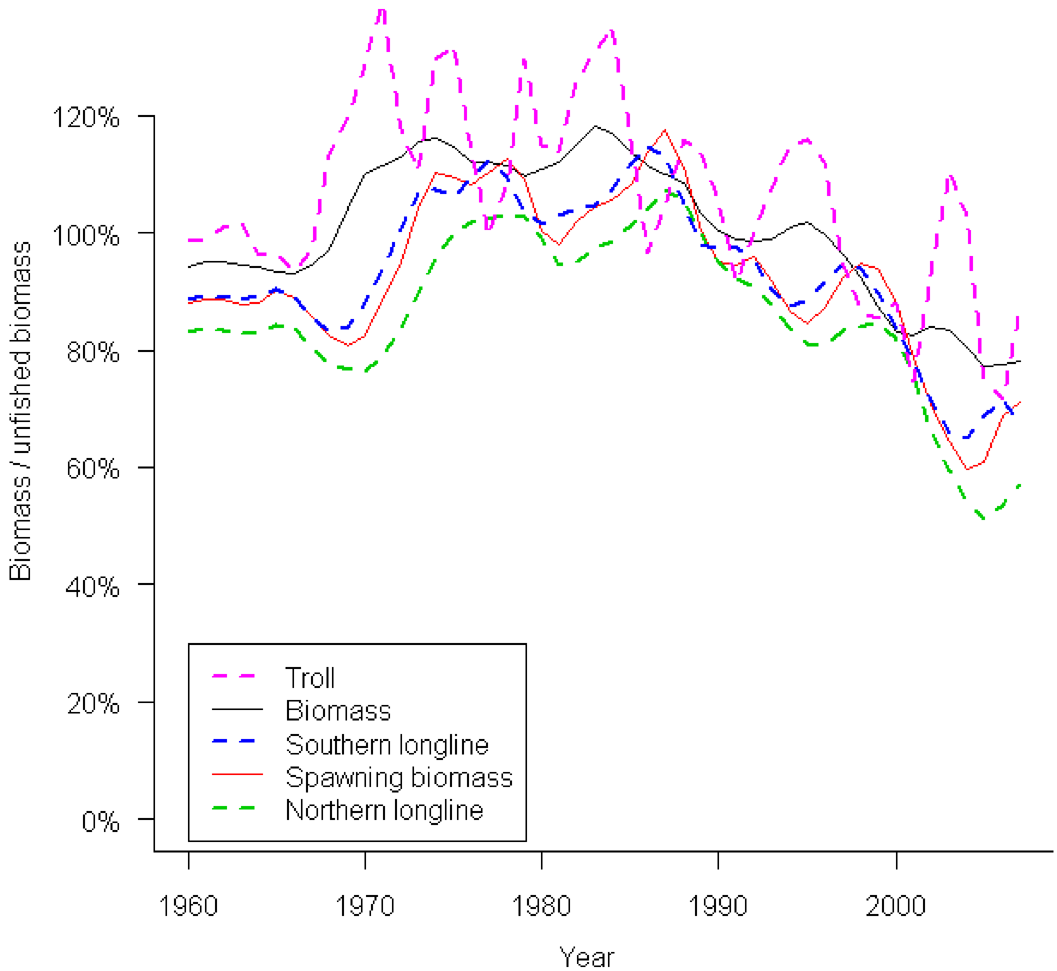


Figure 40: Decline in biomass relative to initial biomass B_0, for exploitable biomass in the troll, southern longline, and northern longline fisheries, for total biomass, and for spawning biomass.

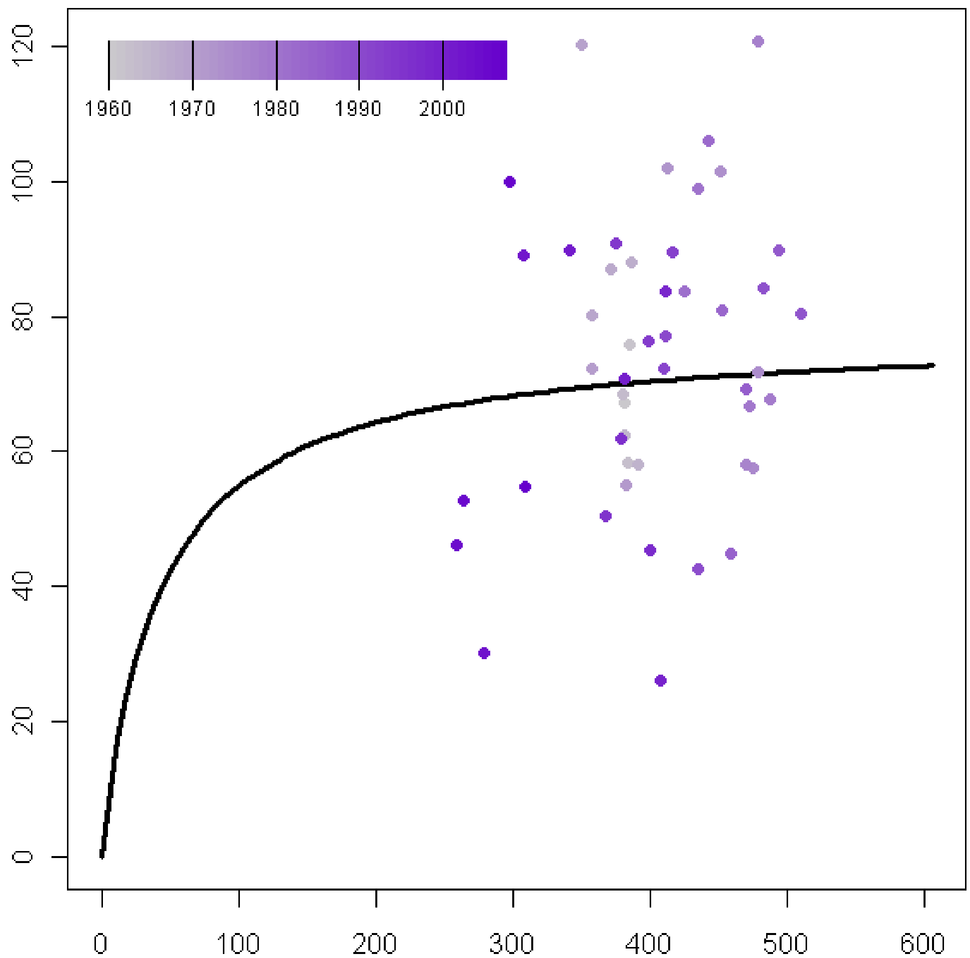


Figure 41. Spawning biomass–recruitment estimates and the fitted Beverton-Holt stock-recruitment relationship (SRR).

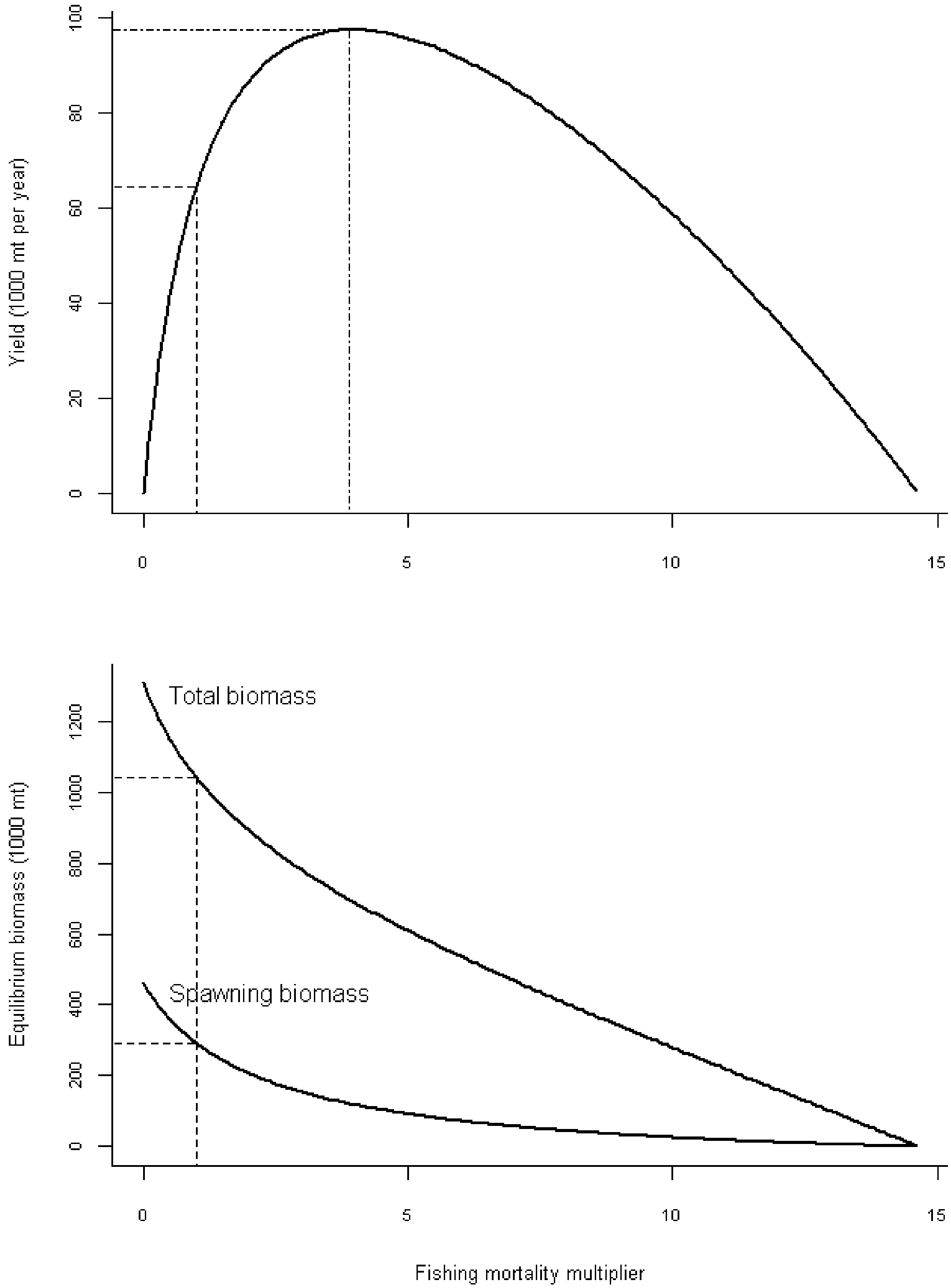


Figure 42: Yield, equilibrium biomass and equilibrium spawning biomass as a function of fishing mortality multiplier. In the top figure, dotted lines indicate equilibrium yield at the current fishing mortality, and maximum sustainable yield. In the lower figure, dotted lines represent equilibrium values of spawning biomass and total biomass at current fishing mortality.

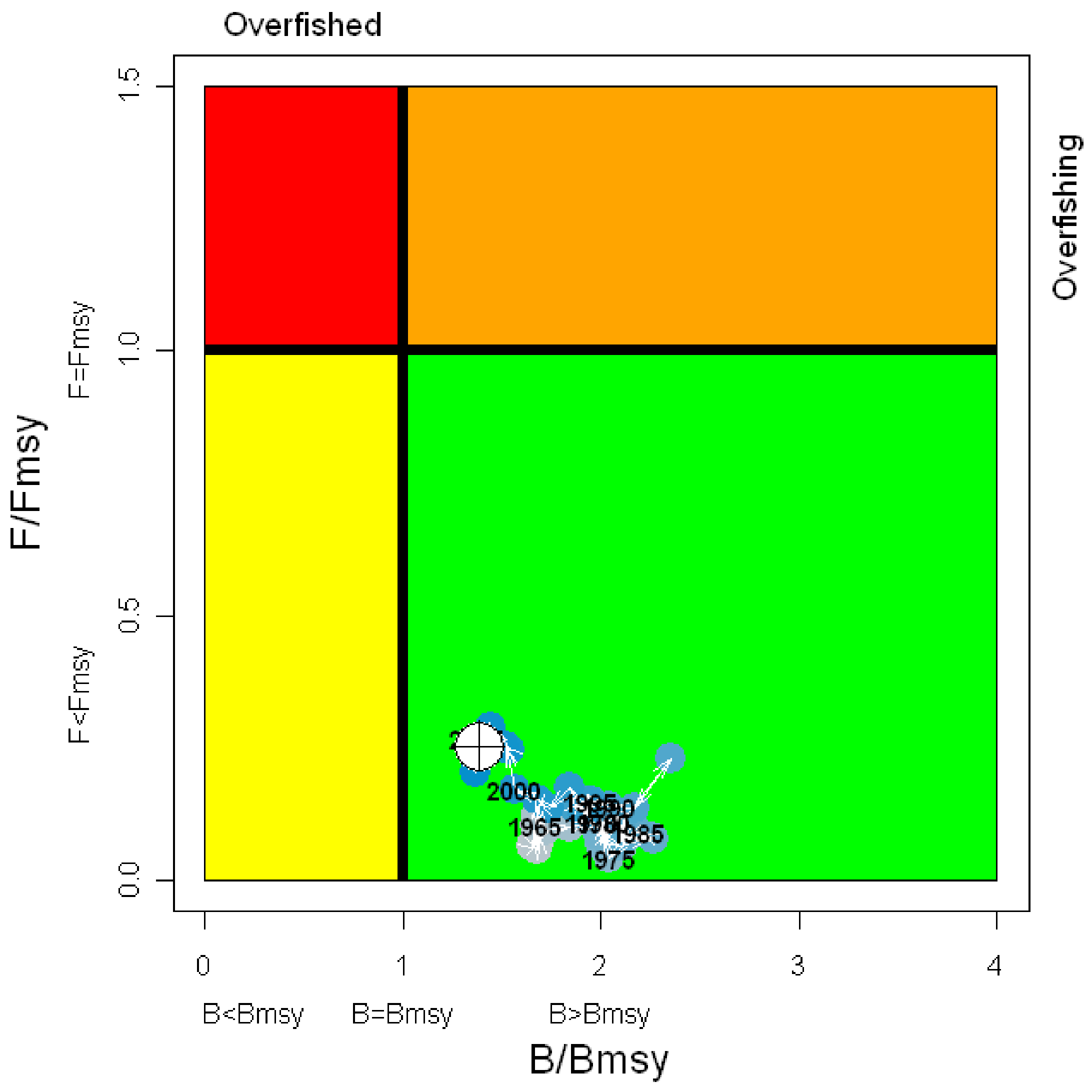


Figure 43: Temporal trend in annual stock status, relative to B_{MSY} (x-axis) and F_{MSY} (y-axis) reference points, for the model period (starting in 1960). The colour of points is graduated from pale blue (1960) to blue (2007), and points are labelled at five-year intervals. The last year of the model (2008) is excluded because it is highly uncertain.

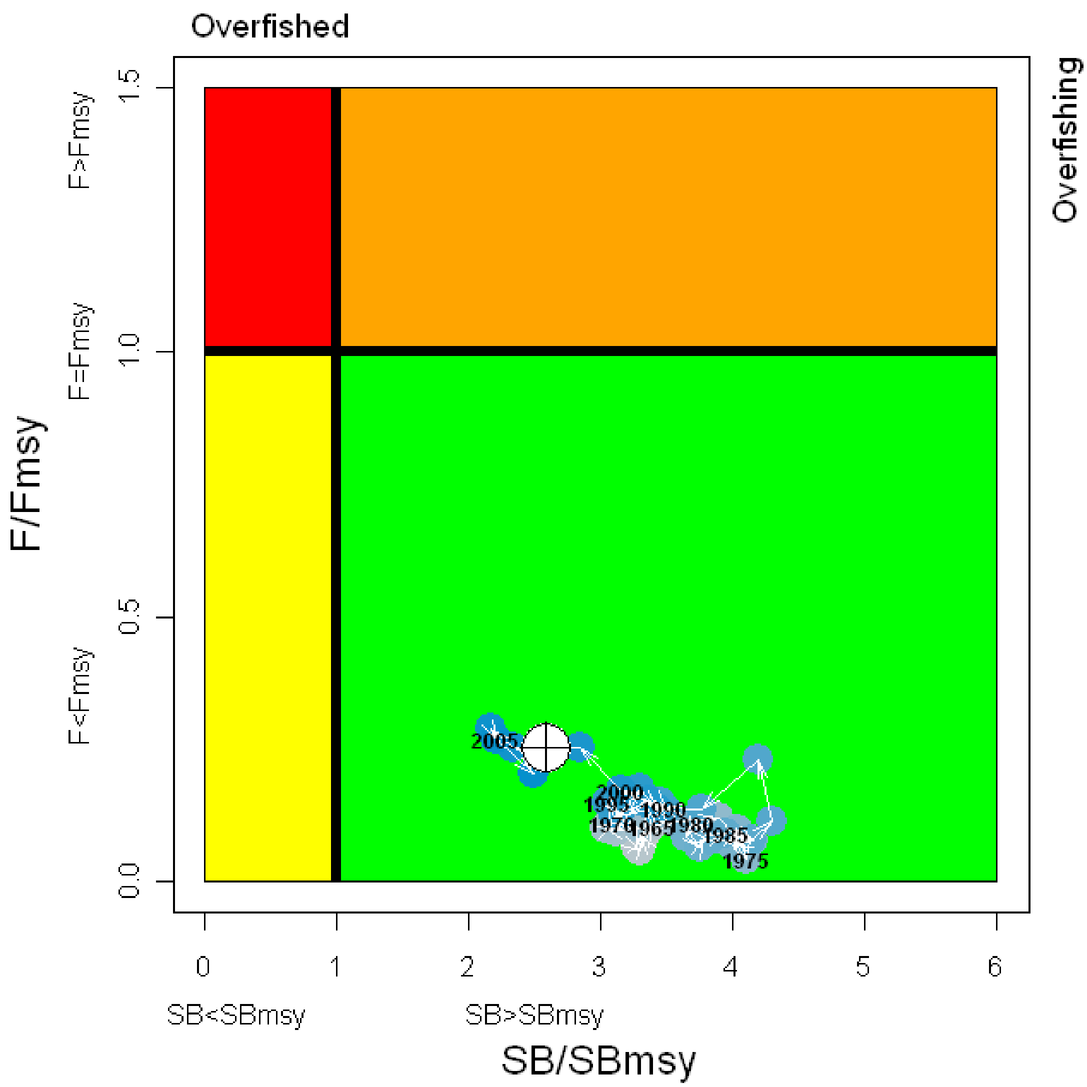


Figure 44: Temporal trend in annual stock status, relative to SB_{MSY} (x-axis) and F_{MSY} (y-axis) reference points, for the model period (starting in 1960). The colour of the points is graduated from pale blue (1960) to blue (2007), and points are labelled at five-year intervals. The last year of the model (2008) is excluded because it is highly uncertain.

.

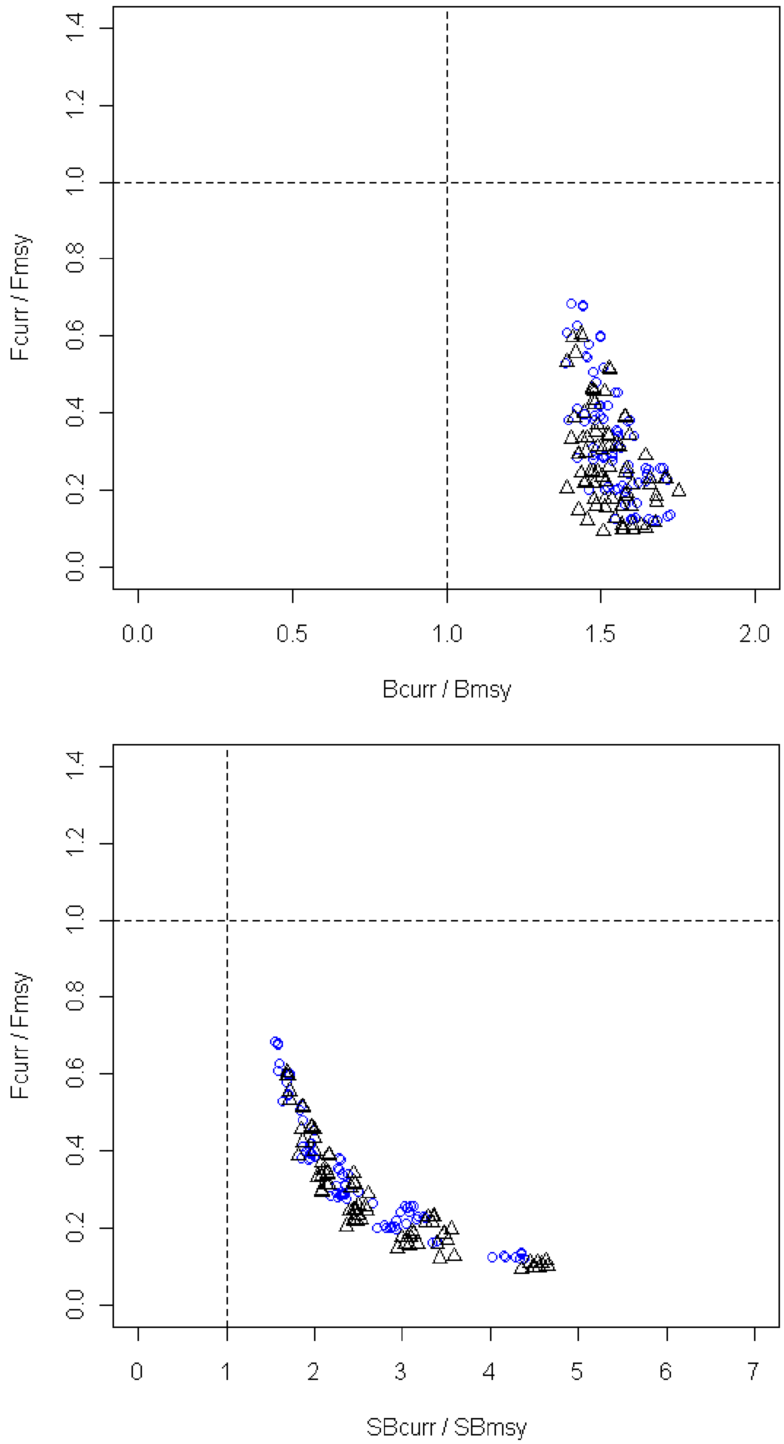


Figure 45: Scatter plots of values estimated under a grid of scenarios for steepness, assumptions about early CPUE, effort creep, natural mortality, start year, and the weight given to the length frequency data. Response variables are a) $F_{2005\text{-}2007}$ / F_{MSY} versus the biomass depletion ratio $B_{2005\text{-}2006}$ / B_{MSY}, and b) $F_{2005\text{-}2007}$ / F_{MSY} versus the spawning biomass depletion ratio $SB_{2005\text{-}2007}$ / SB_{MSY}. Black triangles are for minimal weight given to length frequency data, and blue circles are for the standard weight.

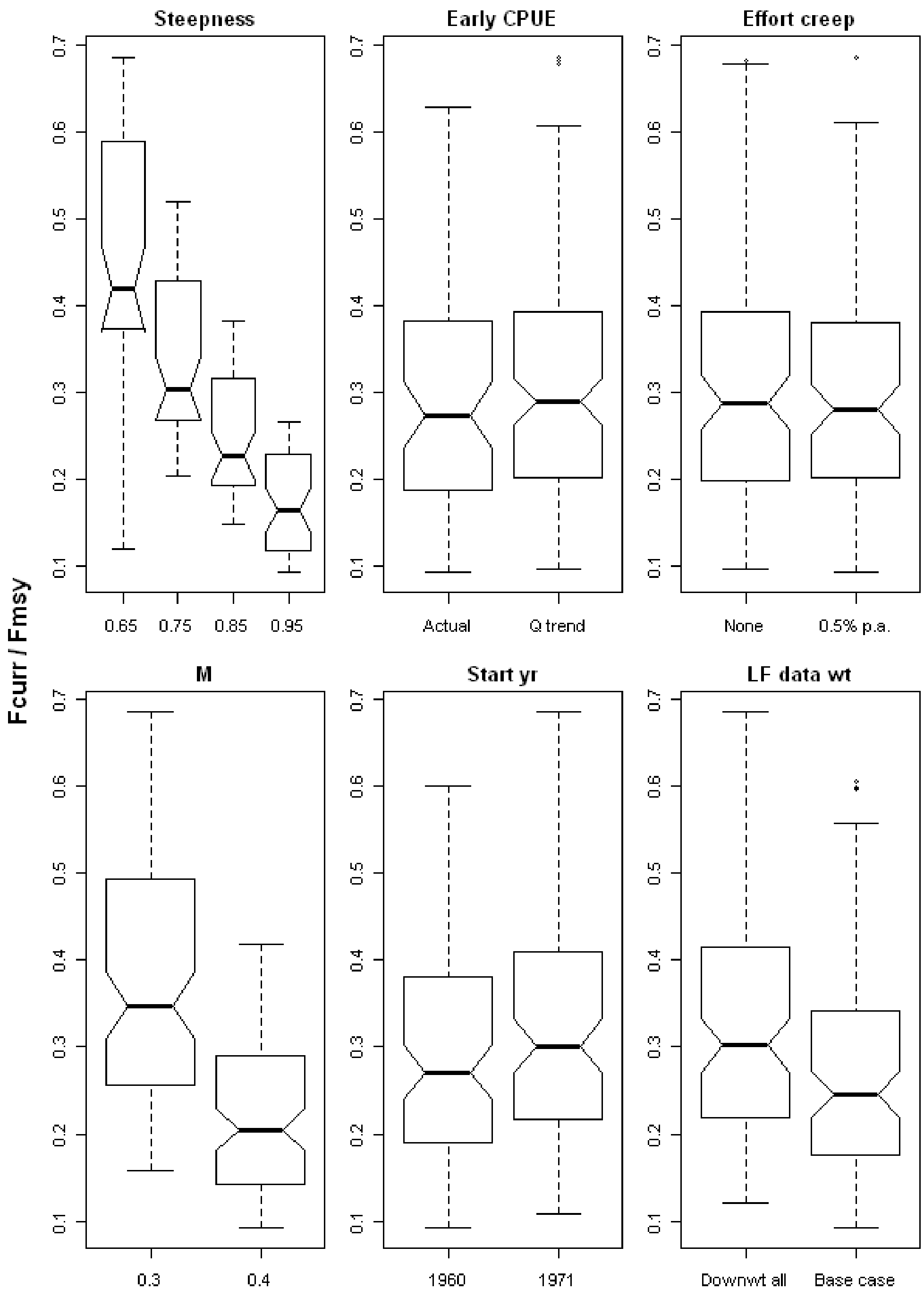


Figure 46: Box and whisker plots indicating the distribution of the fishing mortality ratio $F_{2005\text{-}2007}$ / F_{MSY} estimated under a grid of scenarios for steepness, assumptions about early CPUE, effort creep, natural mortality, start year, and the weight given to the length frequency data.

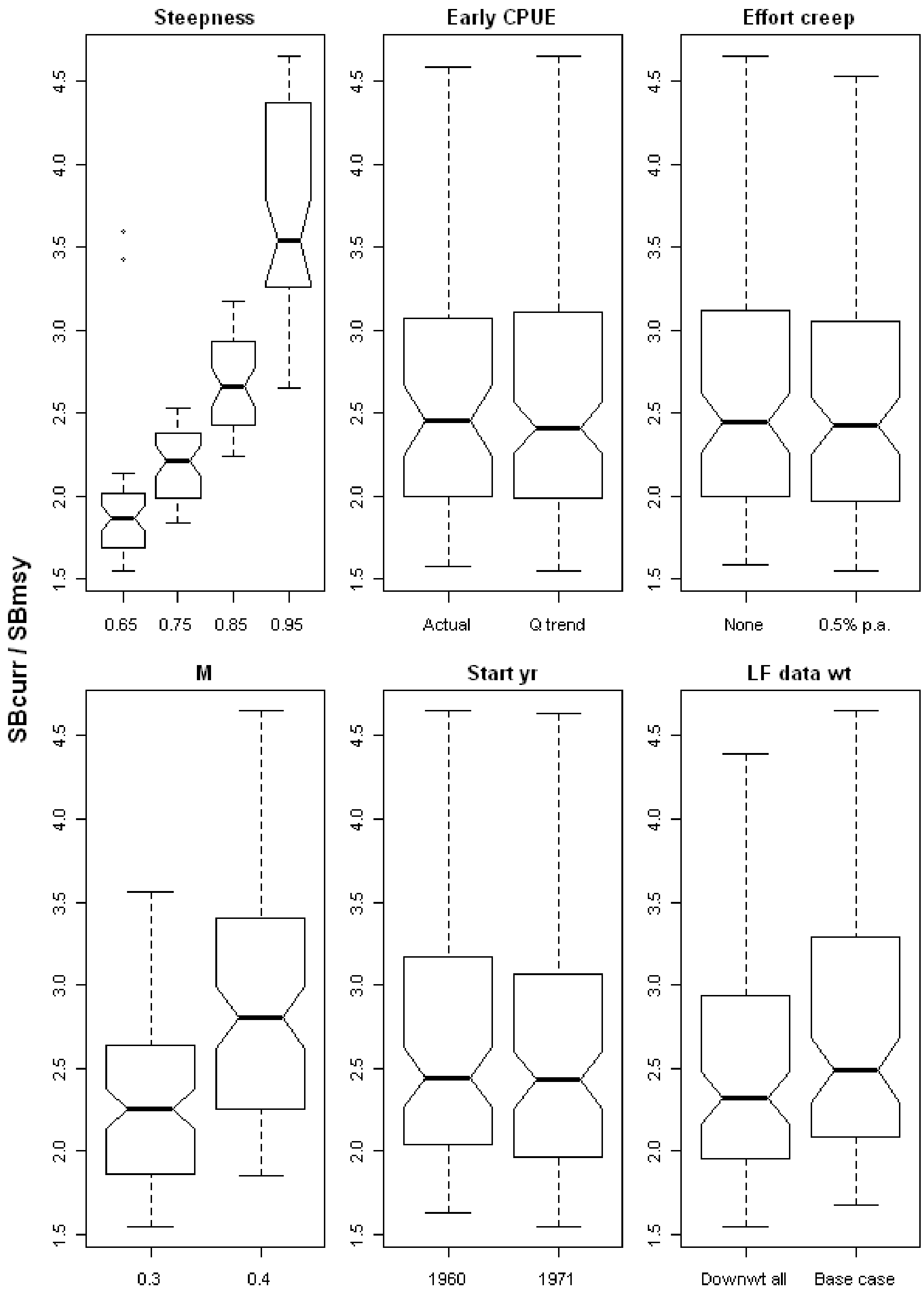


Figure 47: Box and whisker plots indicating the distribution of the spawning biomass depletion ratio SB_{2007} / SB_{MSY} estimated under a grid of scenarios for steepness, assumptions about early CPUE, effort creep, natural mortality, start year, and the weight given to the length frequency data.

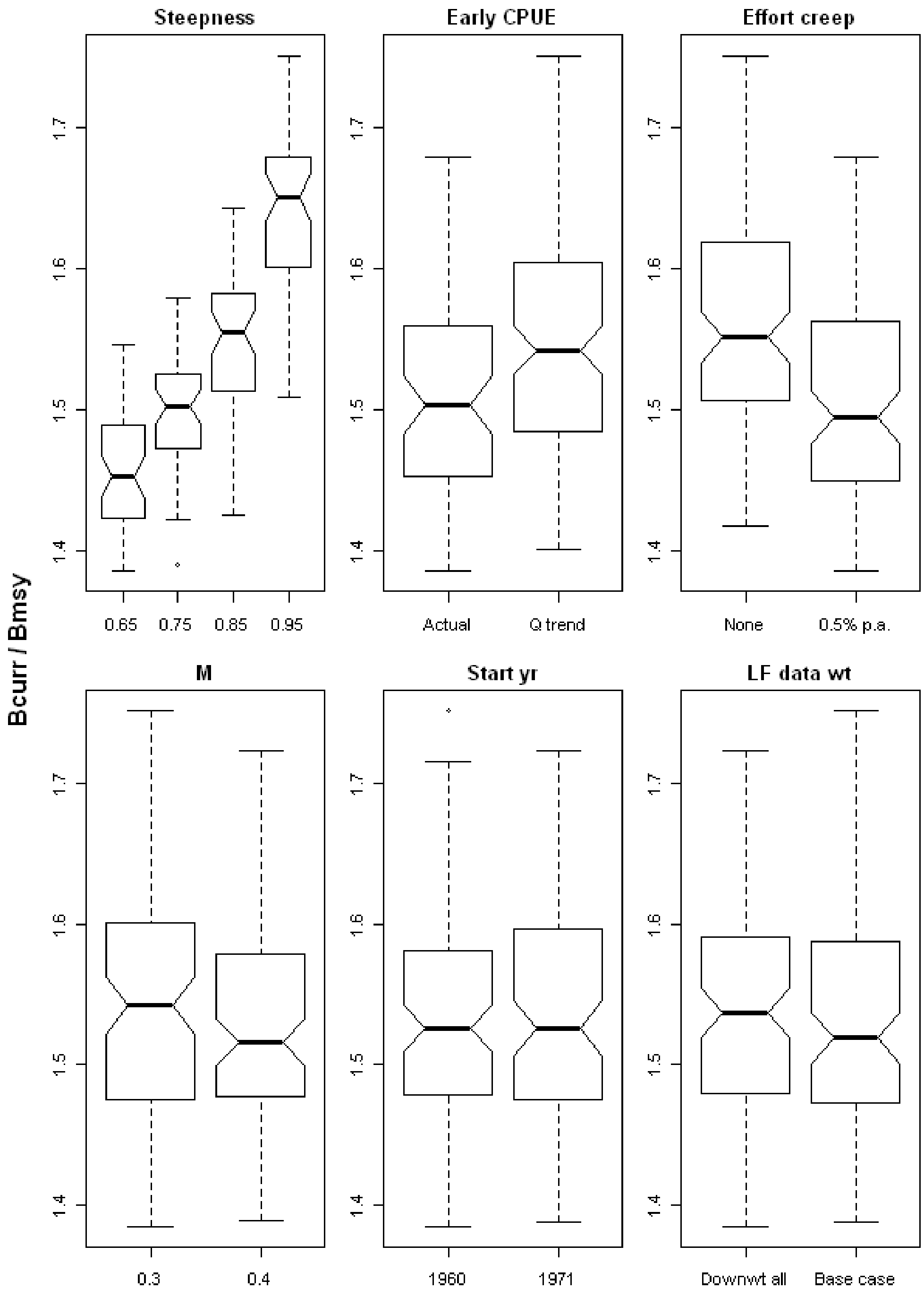


Figure 48: Box and whisker plots indicating the distribution of the biomass depletion ratio $B_{2005-2007}$ / B_{MSY} estimated under a grid of scenarios for steepness, assumptions about early CPUE, effort creep, natural mortality, start year, and the weight given to the length frequency data.

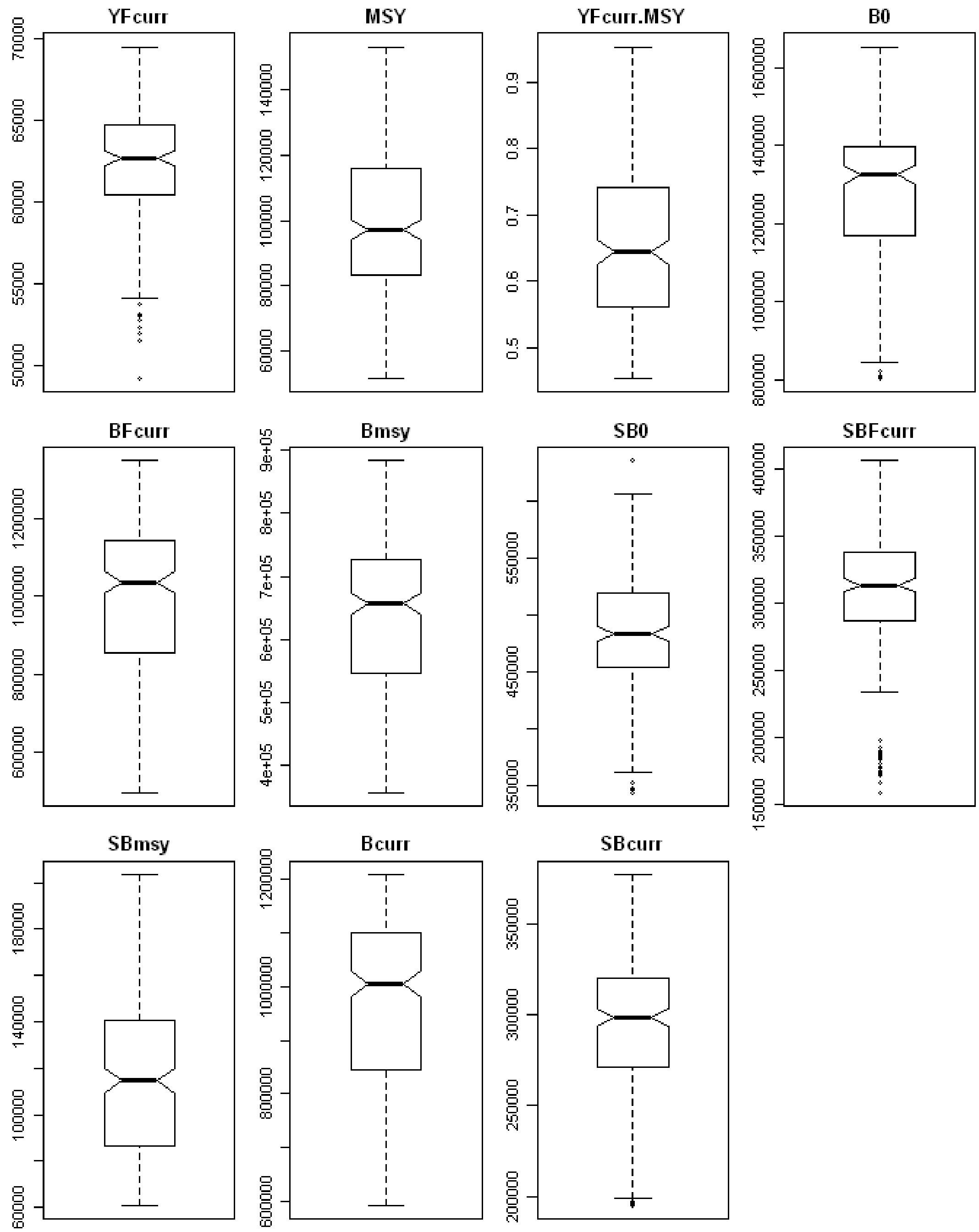


Figure 49: Box and whisker plots indicating the distribution of management-related parameters under a grid of scenarios for steepness, assumptions about early CPUE, effort creep, natural mortality, start year, and the weight given to the length frequency data.

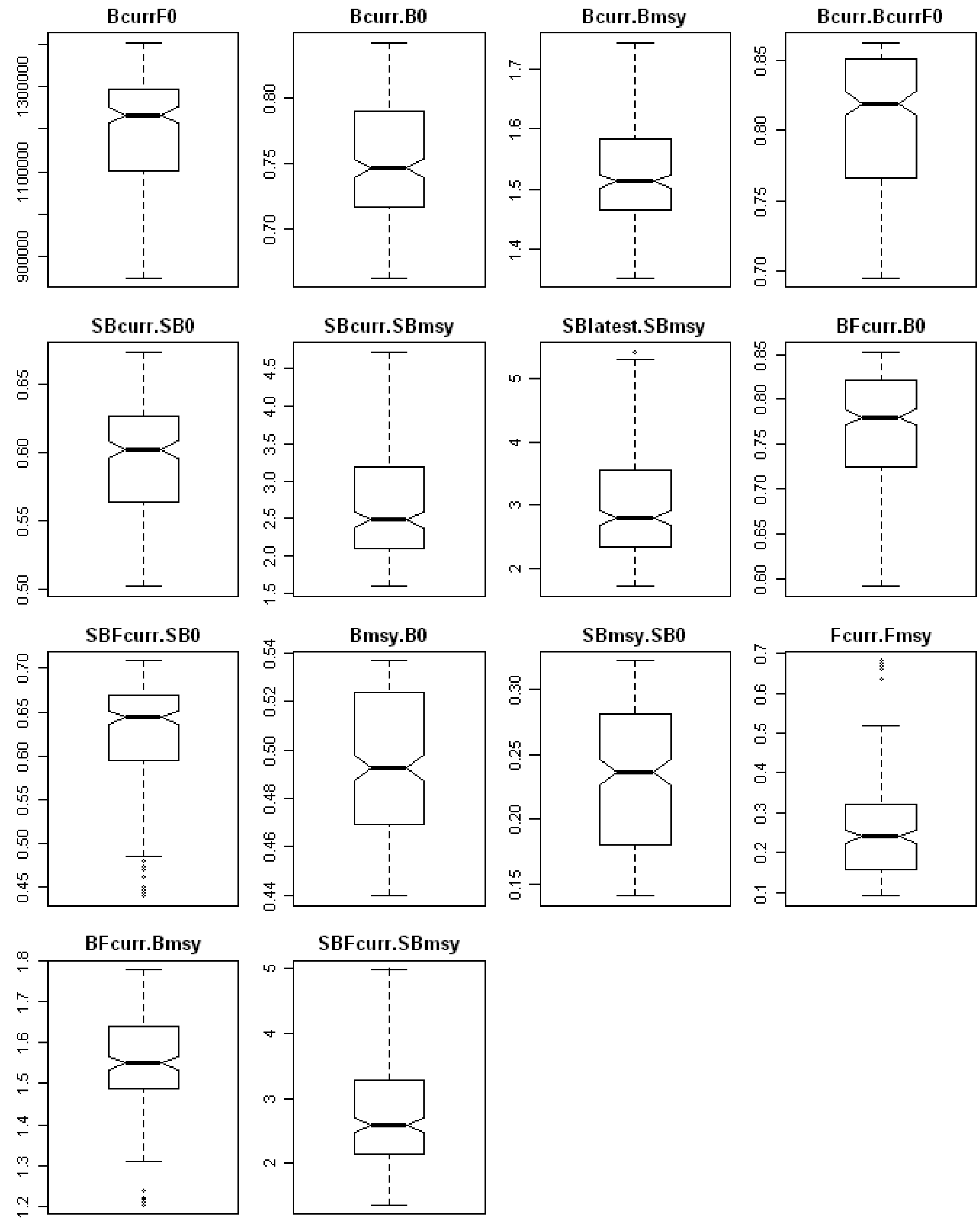


Figure 50: Box and whisker plots indicating the distribution of management-related ratios estimated under a grid of scenarios for steepness, assumptions about early CPUE, effort creep, natural mortality, start year, and the weight given to the length frequency data.

10 Appendix 1: Doitall file

```
#!/bin/sh
export PATH=$PATH:$ADTMP1:/usr/local/lib/
export
LD_LIBRARY_PATH=$LD_LIBRARY_PATH:/u
sr/local/lib
cd $ADTMP1
set

# Apply the recruitment steepness functions changes
to the PAR file.
# $1 Name of the PAR file.
# $2 New value.
function recruitmentConstraints {
   if [ -z $1 ]
   then
    echo "Needs filename as argument.";
    exit 1;
   elif [ -z $2 ]
   then
    echo "Needs new value argument.";
    exit 1;
   elif [ -f "$1" ]
   then
# Read line per line.
    while read LINE
    do
# Found the desired header.
        if [ "$LINE" == "# Seasonal growth
parameters" ]
        then
         echo $LINE >> $1.new;
         for ((L=1 ; L < 2 ; L++))
         do
               read LINE;
# Skip blank or comment line.
               if [[ "$LINE" == "#" || "$LINE" == ""
]]
               then
             #echo "Found a matching line "$LINE;
             L=`expr $L - 1`;
             echo $LINE >> $1.new;
               else
             #echo "Processing line "$LINE;
             I=0;
             for VALUE in $LINE
             do
               I=`expr $I + 1`;
# Change the 29th value.
               if [ $I -eq 29 ]
               then
                echo -n $2" " >> $1.new;
               else
                echo -n $VALUE" " >> $1.new ;
               fi
             done
             echo "" >> $1.new;
            fi
         done
# Write line AS IS.
        else
         echo $LINE >> $1.new;
        fi
    done < $1;
# Create a backup copie.
    mv $1 $1.bak;
# Move temporary file to target file.
    mv $1.new $1;
   fi;
}

# Change the recruitment sd in the PAR file.
# $1 Name of the PAR file.
# $2 New value.
function changeSD {
   if [ -z $1 ]
   then
    echo "Needs filename as argument.";
    exit 1;
   elif [ -z $2 ]
   then
    echo "Needs new value argument.";
    exit 1;
   elif [ -f "$1" ]
   then
# Read line per line.
    while read LINE
    do
# Found the desired header.
        if [ "$LINE" == "# Variance parameters" ]
        then
         echo $LINE >> $1.new;
         for ((L=1 ; L < 2 ; L++))
         do
               read LINE;
# Skip blank or comment line.
               if [[ "$LINE" == "#" || "$LINE" == ""
]]
               then
             #echo "Found a matching line "$LINE;
             L=`expr $L - 1`;
             echo $LINE >> $1.new;
               else
```

```
            #echo "Processing line "$LINE;
            I=0;
            for VALUE in $LINE
            do
              I=`expr $I + 1`;
# Change the 29th value.
              if [ $I -eq 1 ]
              then
               echo -n $2" " >> $1.new;
              else
               echo -n $VALUE" " >> $1.new ;
              fi
            done
            echo "" >> $1.new;
           fi
         done
# Write line AS IS.
        else
         echo $LINE >> $1.new;
        fi
     done < $1;
# Create a backup copie.
     mv $1 $1.bak;
# Move temporary file to target file.
     mv $1.new $1;
    fi;
}

# SOUTH PACIFIC ALBACORE ANALYSIS
1952-2002 data (by quarter **)
#
# Definition of regions
#
# Region 1: 0-30S, 140E-180
# Region 2: 0-30S, 180-90W
# Region 3: 30S-50S, 140E-180
# Region 4: 30S-50S, 180-90W
#
# Definition of fisheries
#
# Fishery   Gear   Nation         Region
#    1      L      JP,JPDW        1
#    2      L      KR             1
#    3      L      TWDW           1
#    4      L      AU             1
#    5      L      NC             1
#    6      L      FJ             1
#    7      L      OT             1
#    8      L      JP,JPDW        2
#    9      L      KR             2
#   10      L      TWDW           2
#   11      L      AS,WS          2
#   12      L      TO             2
#   13      L      PF             2
#   14      L      OT             2
#   15      L      JP,JPDW        3
#   16      L      KR             3
#   17      L      TWDW           3
#   18      L      AU             3
#   19      L      NZ             3
#   20      L      OT             3
#   21      L      JP,JPDW        4
#   22      L      KR             4
#   23      L      TWDW           4
#   24      L      OT             4
#   25      T      ALL            3
#   26      T      ALL            4
#   27      D      ALL            3
#   28      D      ALL            4
#   29      L      ALL            5
#   30      L      ALL            6
#
#  ------------------------
#  Create initial par file
#  ------------------------
 ./mfclo32 alb.frq alb.ini 00.par -makepar
#  ------------------------
#  Initial fit conditions
#  ------------------------
#if [ ! -f 01.par ]; then
 ./mfclo32 alb.frq 00.par 01.par -file - <<PHASE1
 2 32 1
 1 32 6      # sets "no vonB" initial estimation
 1 111 2     # likelihood function for tags = poisson
 1 141 3     # likelihood function for LF data =
normal
 2 57 1      # set no. of recruitments per year to 1
 2 93 1      # set no. of recruitments per year to 1
 2 69 1      # sets generic movement option
 2 94 2      # equilibrium calculation of initial
population based on Z
 2 95 3      # uses average Z over 1st 3 years
# 2 94 1       # equilibrium calculation of initial
population based on M
# 2 95 10      # uses 1 times the initial M
 -999 26 2   # length-dependent selectivity
 -999 33 1   # estimate tag-reporting rate
 1 33 90     # maximum tag reporting rate is 0.9
 -999 35 1   # penalty on reporting rate, i.e. prior is
uninformative
 -999 36 10  # prior for reporting rate is 0.1
 -999 13 -10 # sets penalty weights for effort devs
 -999 15 50  # sets penalty weights for q devs
 -9999 1 4   # sets first tag flag to 4 (no. mixing
periods) for all
#            tag release sets (** was 1 before)
# grouping of fisheries for tag reporting rate
  -1 34 1
  -2 34 1
  -3 34 1
  -4 34 1
  -5 34 2
```

-6 34 2
-7 34 2
-8 34 2
-9 34 2
-10 34 2
-11 34 2
-12 34 2
-13 34 3
-14 34 3
-15 34 3
-16 34 3
-17 34 3
-18 34 3
-19 34 3
-20 34 3
-21 34 4
-22 34 4
-23 34 4
-24 34 4
-25 34 5
-26 34 5
-27 34 5
-28 34 5
-29 34 6
-30 34 6
-31 34 6
-32 34 6
-33 34 7
-34 34 7
-35 34 7
-36 34 7
-37 34 8
-38 34 8
-39 34 8
-40 34 8
-41 34 9
-42 34 9
-43 34 9
-44 34 9
-45 34 9
-46 34 9
-47 34 9
-48 34 9
-49 34 9
-50 34 9
-51 34 9
-52 34 9
-53 34 10
-54 34 10
-55 34 10
-56 34 10
-57 34 10
-58 34 10
-59 34 10
-60 34 10
-61 34 10
-62 34 10
-63 34 10
-64 34 10
-65 34 11
-66 34 11
-67 34 11
-68 34 11
-69 34 12
-70 34 12
-71 34 12
-72 34 12
-73 34 13
-74 34 13
-75 34 13
-76 34 13
-77 34 14
-78 34 14
-79 34 14
-80 34 14
-81 34 15
-82 34 15
-83 34 15
-84 34 15
-85 34 15
-86 34 15
-87 34 15
-88 34 15
-89 34 16
-90 34 16
-91 34 16
-92 34 16
-93 34 17
-94 34 17
-95 34 17
-96 34 17
-97 34 18
-98 34 18
-99 34 18
-100 34 18
-101 34 19
-102 34 19
-103 34 19
-104 34 19
-105 34 20
-106 34 20
-107 34 20
-108 34 20
-109 34 21
-110 34 21
-111 34 21
-112 34 21
-113 34 21
-114 34 21
-115 34 21
-116 34 21
-117 34 22

-118 34 22
-119 34 22
-120 34 22
-121 34 22
-122 34 22
-123 34 22
-124 34 22
-125 34 23
-126 34 23
-127 34 23
-128 34 23
-129 34 23
-130 34 23
-131 34 23
-132 34 23
-133 34 24
-134 34 24
-135 34 24
-136 34 24
-137 34 25
-138 34 26
-139 34 27
-140 34 28
-141 34 27
-142 34 27
-143 34 27
-144 34 27
-145 34 28
-146 34 28
-147 34 28
-148 34 28
sets non-decreasing selectivity for longline fisheries
-1 16 0
-2 16 0
-3 16 0
-4 16 0
-5 16 0
-6 16 0
-7 16 0
-8 16 0
-9 16 0
-10 16 0
-11 16 0
-12 16 0
-13 16 0
-14 16 0
-15 16 0
-16 16 0
-17 16 0
-18 16 0
-19 16 0
-20 16 0
-21 16 0
-22 16 0
-23 16 0
-24 16 0
-25 16 0
-26 16 0
-27 16 0
-28 16 0
-29 16 0
-30 16 0
-31 16 0
-32 16 0
-33 16 0
-34 16 0
-35 16 0
-36 16 0
-37 16 0
-38 16 0
-39 16 0
-40 16 0
-41 16 0
-42 16 0
-43 16 0
-44 16 0
-45 16 0
-46 16 0
-47 16 0
-48 16 0
-49 16 0
-50 16 1
-51 16 1
-52 16 1
-53 16 0
-54 16 0
-55 16 0
-56 16 0
-57 16 0
-58 16 0
-59 16 0
-60 16 0
-61 16 0
-62 16 1
-63 16 1
-64 16 1
-65 16 0
-66 16 0
-67 16 0
-68 16 0
-69 16 0
-70 16 0
-71 16 0
-72 16 0
-73 16 0
-74 16 0
-75 16 0
-76 16 1
-77 16 0
-78 16 0
-79 16 0

-80 16 0
-81 16 0
-82 16 0
-83 16 0
-84 16 0
-85 16 0
-86 16 0
-87 16 0
-88 16 0
-89 16 0
-90 16 0
-91 16 0
-92 16 0
-93 16 0
-94 16 0
-95 16 0
-96 16 0
-97 16 0
-98 16 0
-99 16 0
-100 16 0
-101 16 0
-102 16 0
-103 16 0
-104 16 0
-105 16 0
-106 16 0
-107 16 0
-108 16 0
-109 16 0
-110 16 0
-111 16 0
-112 16 0
-113 16 0
-114 16 0
-115 16 0
-116 16 0
-117 16 0
-118 16 0
-119 16 0
-120 16 0
-121 16 0
-122 16 0
-123 16 0
-124 16 0
-125 16 0
-126 16 0
-127 16 0
-128 16 0
-129 16 0
-130 16 0
-131 16 0
-132 16 0
-133 16 0
-134 16 0
-135 16 0
-136 16 0
-141 16 0
-142 16 0
-143 16 0
-144 16 0
-145 16 0
-146 16 0
-147 16 0
-148 16 0
sets zero selectivity for age classes 19 and 20 in troll fisheries
-137 16 2
-138 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
-2 24 2
-3 24 3
-4 24 4
-5 24 5
-6 24 6
-7 24 7
-8 24 8
-9 24 9
-10 24 10
-11 24 11
-12 24 12
-13 24 13
-14 24 14
-15 24 15
-16 24 16
-17 24 17
-18 24 18
-19 24 19
-20 24 20
-21 24 21
-22 24 22
-23 24 23
-24 24 24
-25 24 25
-26 24 26
-27 24 27
-28 24 28
-29 24 29
-30 24 30
-31 24 31
-32 24 32
-33 24 33
-34 24 34
-35 24 35
-36 24 36
-37 24 37
-38 24 38
-39 24 39

-40 24 40
-41 24 41
-42 24 42
-43 24 43
-44 24 44
-45 24 45
-46 24 46
-47 24 47
-48 24 48
-49 24 49
-50 24 50
-51 24 51
-52 24 52
-53 24 53
-54 24 54
-55 24 55
-56 24 56
-57 24 57
-58 24 58
-59 24 59
-60 24 60
-61 24 61
-62 24 62
-63 24 63
-64 24 64
-65 24 65
-66 24 66
-67 24 67
-68 24 68
-69 24 69
-70 24 70
-71 24 71
-72 24 72
-73 24 73
-74 24 74
-75 24 75
-76 24 76
-77 24 77
-78 24 78
-79 24 79
-80 24 80
-81 24 81
-82 24 82
-83 24 83
-84 24 84
-85 24 85
-86 24 86
-87 24 87
-88 24 88
-89 24 89
-90 24 90
-91 24 91
-92 24 92
-93 24 93
-94 24 94
-95 24 95
-96 24 96
-97 24 97
-98 24 98
-99 24 99
-100 24 100
-101 24 101
-102 24 102
-103 24 103
-104 24 104
-105 24 105
-106 24 106
-107 24 107
-108 24 108
-109 24 109
-110 24 110
-111 24 111
-112 24 112
-113 24 113
-114 24 114
-115 24 115
-116 24 116
-117 24 117
-118 24 118
-119 24 119
-120 24 120
-121 24 121
-122 24 122
-123 24 123
-124 24 124
-125 24 125
-126 24 126
-127 24 127
-128 24 128
-129 24 129
-130 24 130
-131 24 131
-132 24 132
-133 24 133
-134 24 134
-135 24 135
-136 24 136
-137 24 137
-138 24 138
-139 24 139
-140 24 139
-141 24 140
-142 24 141
-143 24 142
-144 24 143
-145 24 144
-146 24 145
-147 24 146
-148 24 147
#use cubic spline for selectivity
-999 57 3
-999 61 4 #number of parameters in cubic spline

#catchability groupings
-1 29 1
-2 29 2
-3 29 3
-4 29 4
-5 29 5
-6 29 5
-7 29 6
-8 29 6
-9 29 7
-10 29 7
-11 29 8
-12 29 8
-13 29 9
-14 29 9
-15 29 10
-16 29 10
-17 29 11
-18 29 11
-19 29 12
-20 29 12
-21 29 13
-22 29 14
-23 29 15
-24 29 16
-25 29 17
-26 29 18
-27 29 19
-28 29 20
-29 29 21
-30 29 22
-31 29 23
-32 29 24
-33 29 25
-34 29 26
-35 29 27
-36 29 28
-37 29 29
-38 29 30
-39 29 31
-40 29 32
-41 29 33
-42 29 33
-43 29 33
-44 29 34
-45 29 34
-46 29 34
-47 29 35
-48 29 35
-49 29 35
-50 29 36
-51 29 36
-52 29 36
-53 29 37
-54 29 37
-55 29 37
-56 29 38
-57 29 38
-58 29 38
-59 29 39
-60 29 39
-61 29 39
-62 29 40
-63 29 40
-64 29 40
-65 29 41
-66 29 42
-67 29 43
-68 29 44
-69 29 45
-70 29 46
-71 29 47
-72 29 48
-73 29 49
-74 29 50
-75 29 51
-76 29 52
-77 29 53
-78 29 54
-79 29 55
-80 29 56
-81 29 57
-82 29 57
-83 29 58
-84 29 58
-85 29 59
-86 29 59
-87 29 60
-88 29 60
-89 29 61
-90 29 62
-91 29 63
-92 29 64
-93 29 65
-94 29 66
-95 29 67
-96 29 68
-97 29 69
-98 29 70
-99 29 71
-100 29 72
-101 29 73
-102 29 74
-103 29 75
-104 29 76
-105 29 77
-106 29 78
-107 29 79
-108 29 80
-109 29 81
-110 29 81
-111 29 82

-112 29 82
-113 29 83
-114 29 83
-115 29 84
-116 29 84
-117 29 85
-118 29 85
-119 29 86
-120 29 86
-121 29 87
-122 29 87
-123 29 88
-124 29 88
-125 29 89
-126 29 89
-127 29 90
-128 29 90
-129 29 91
-130 29 91
-131 29 92
-132 29 92
-133 29 93
-134 29 94
-135 29 95
-136 29 96
-137 29 97
-138 29 98
-139 29 99
-140 29 100
-141 29 101
-142 29 102
-143 29 103
-144 29 104
-145 29 105
-146 29 106
-147 29 107
-148 29 108
-1 60 1
-2 60 2
-3 60 3
-4 60 4
-5 60 5
-6 60 5
-7 60 6
-8 60 6
-9 60 7
-10 60 7
-11 60 8
-12 60 8
-13 60 9
-14 60 9
-15 60 10
-16 60 10
-17 60 11
-18 60 11
-19 60 12
-20 60 12
-21 60 13
-22 60 14
-23 60 15
-24 60 16
-25 60 17
-26 60 18
-27 60 19
-28 60 20
-29 60 21
-30 60 22
-31 60 23
-32 60 24
-33 60 25
-34 60 26
-35 60 27
-36 60 28
-37 60 29
-38 60 30
-39 60 31
-40 60 32
-41 60 33
-42 60 33
-43 60 33
-44 60 34
-45 60 34
-46 60 34
-47 60 35
-48 60 35
-49 60 35
-50 60 36
-51 60 36
-52 60 36
-53 60 37
-54 60 37
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-56 60 38
-57 60 38
-58 60 38
-59 60 39
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-62 60 40
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-67 60 43
-68 60 44
-69 60 45
-70 60 46
-71 60 47
-72 60 48
-73 60 49
-74 60 50
-75 60 51

-76 60 52
-77 60 53
-78 60 54
-79 60 55
-80 60 56
-81 60 57
-82 60 109
-83 60 58
-84 60 110
-85 60 59
-86 60 111
-87 60 60
-88 60 112
-89 60 61
-90 60 62
-91 60 63
-92 60 64
-93 60 65
-94 60 66
-95 60 67
-96 60 68
-97 60 69
-98 60 70
-99 60 71
-100 60 72
-101 60 73
-102 60 74
-103 60 75
-104 60 76
-105 60 77
-106 60 78
-107 60 79
-108 60 80
-109 60 81
-110 60 113
-111 60 82
-112 60 114
-113 60 83
-114 60 115
-115 60 84
-116 60 116
-117 60 85
-118 60 85
-119 60 86
-120 60 86
-121 60 87
-122 60 87
-123 60 88
-124 60 88
-125 60 89
-126 60 89
-127 60 90
-128 60 90
-129 60 91
-130 60 91
-131 60 92
-132 60 92
-133 60 93
-134 60 94
-135 60 95
-136 60 96
-137 60 97
-138 60 98
-139 60 99
-140 60 100
-141 60 101
-142 60 102
-143 60 103
-144 60 104
-145 60 105
-146 60 106
-147 60 107
-148 60 108
1 12 0
1 13 0
1 14 0
1 15 0
1 173 5
1 184 0
1 227 0
1 12 0
1 13 0
1 14 0
1 15 0
1 16 0
1 173 5
1 184 0
1 227 0
-1 13 1
-2 13 1
-3 13 1
-4 13 1
-5 13 1
-6 13 1
-7 13 1
-8 13 1
-9 13 1
-10 13 1
-11 13 1
-12 13 1
-13 13 1
-14 13 1
-15 13 1
-16 13 1
-17 13 1
-18 13 1
-19 13 1
-20 13 1
-37 13 1
-38 13 1
-39 13 1
-40 13 1

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-41 13 1
-42 13 1
-43 13 1
-44 13 1
-45 13 1
-46 13 1
-47 13 1
-48 13 1
-49 13 1
-50 13 1
-51 13 1
-52 13 1
-53 13 1
-54 13 1
-55 13 1
-56 13 1
-57 13 1
-58 13 1
-59 13 1
-60 13 1
-61 13 1
-62 13 1
-63 13 1
-64 13 1
-81 13 1
-82 13 1
-83 13 1
-84 13 1
-85 13 1
-86 13 1
-87 13 1
-88 13 1
-89 13 1
-90 13 1
-91 13 1
-92 13 1
-93 13 1
-94 13 1
-95 13 1
-96 13 1
-109 13 1
-110 13 1
-111 13 1
-112 13 1
-113 13 1
-114 13 1
-115 13 1
-116 13 1
-117 13 1
-118 13 1
-119 13 1
-120 13 1
-121 13 1
-122 13 1
-123 13 1
-124 13 1
 -125 13 1
 -126 13 1
 -127 13 1
 -128 13 1
 -129 13 1
 -130 13 1
 -131 13 1
 -132 13 1
 -141 13 1
 -142 13 1
 -143 13 1
 -144 13 1
 -145 13 1
 -146 13 1
 -147 13 1
 -148 13 1
 -97 11 1
 -98 11 1
PHASE1
recruitmentConstraints 01.par 0.75
 ./mfclo32 alb.frq 01.par 02.par -file - <<PHASE2
 1 149 100
 -999 3 19   # 1st age class of 20 where selectivity held fixed
 -999 4 2    # turn on effort dev estimation
 1 189 1     # write graph.frq file (LF observed and predicted)
 1 190 1     # write plot.rep
 1 1 100     # no. function evaluations
PHASE2
#
 ./mfclo32 alb.frq 02.par 03.par -file - <<PHASE3
 1 1 100     # no. function evaluations
 1 50 -6      # sets convergence criterion to 1E-6
  -999 49 20
PHASE3
#
# estimate seasonal catchability
 ./mfclo32 alb.frq 03.par 04.par -file - <<PHASE4
 -999 27 1   # estimate seasonal catchability
  2 35 10
  -137 49 10
  -138 49 10
  -139 49 10
  -140 49 10
  -81 49 60
  -82 49 60
  -83 49 60
  -84 49 60
  -85 49 60
  -86 49 60
  -87 49 60
  -88 49 60
  -89 49 60
  -90 49 60
  -91 49 60
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-92 49 60
-93 49 60
-94 49 60
-95 49 60
-96 49 60
-97 49 60
-98 49 60
-99 49 60
-100 49 60
-105 49 60
-106 49 60
-107 49 60
-108 49 60
-109 49 60
-110 49 60
-111 49 60
-112 49 60
-113 49 60
-114 49 60
-115 49 60
-116 49 60
-117 49 60
-118 49 60
-119 49 60
-120 49 60
-121 49 60
-122 49 60
-123 49 60
-124 49 60
-125 49 60
-126 49 60
-127 49 60
-128 49 60
-129 49 60
-130 49 60
-131 49 60
-132 49 60
-133 49 60
-134 49 60
-135 49 60
-136 49 60
-145 49 60
-146 49 60
-147 49 60
-148 49 60
-21 49 120
-22 49 120
-23 49 120
-24 49 120
-25 49 120
-26 49 120
-27 49 120
-28 49 120
-33 49 120
-34 49 120
-35 49 120
 -36 49 120
 -77 49 120
 -78 49 120
 -79 49 120
 -80 49 120
 -97 49 120
 -98 49 120
 -99 49 120
 -100 49 120
 -105 49 120
 -106 49 120
 -107 49 120
 -108 49 120
 -133 49 120
 -134 49 120
 -135 49 120
 -136 49 120
 -29 49 40
 -30 49 40
 -31 49 40
 -32 49 40
 -73 49 40
 -74 49 40
 -75 49 40
 -76 49 40
PHASE4
#
# estimate catchability time series
 ./mfclo32 alb.frq 04.par 05.par -file - <<PHASE5
 -999 10 1   # estimate time-series catchability
  -1 10 0
  -2 10 0
  -3 10 0
  -4 10 0
  -5 10 0
  -6 10 0
  -7 10 0
  -8 10 0
  -9 10 0
  -10 10 0
  -11 10 0
  -12 10 0
  -13 10 0
  -14 10 0
  -15 10 0
  -16 10 0
  -17 10 0
  -18 10 0
  -19 10 0
  -20 10 0
  -37 10 0
  -38 10 0
  -39 10 0
  -40 10 0
  -41 10 0
  -42 10 0
```

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-43 10 0
-44 10 0
-45 10 0
-46 10 0
-47 10 0
-48 10 0
-49 10 0
-50 10 0
-51 10 0
-52 10 0
-53 10 0
-54 10 0
-55 10 0
-56 10 0
-57 10 0
-58 10 0
-59 10 0
-60 10 0
-61 10 0
-62 10 0
-63 10 0
-64 10 0
-81 10 0
-82 10 0
-83 10 0
-84 10 0
-85 10 0
-86 10 0
-87 10 0
-88 10 0
-89 10 0
-90 10 0
-91 10 0
-92 10 0
-93 10 0
-94 10 0
-95 10 0
-96 10 0
-109 10 0
-110 10 0
-111 10 0
-112 10 0
-113 10 0
-114 10 0
-115 10 0
-116 10 0
-117 10 0
-118 10 0
-119 10 0
-120 10 0
-121 10 0
-122 10 0
-123 10 0
-124 10 0
-125 10 0
-126 10 0
  -127 10 0
  -128 10 0
  -129 10 0
  -130 10 0
  -131 10 0
  -132 10 0
  -999 23 11
 -999 15 1
 1 1 500     # no. function evaluations
 1 50 -6      # sets convergence criterion to 1E-6
  -137 10 1
PHASE5
#
 ./mfclo32 alb.frq 05.par 06.par -file - <<PHASE6
 2 82 40     # prior for M is 40/100
 2 84 0      # no penalty for prior
 1 1 100     # no. function evaluations
 1 50 -6      # sets convergence criterion to 1E-6
PHASE6
#
 ./mfclo32 alb.frq 06.par 07.par -file - <<PHASE7
 1 1 100     # no. function evaluations
 1 50 -6      # sets convergence criterion to 1E-6
  1 12 1
  1 184 1
  1 182 10
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 5000     # no. function evaluations
  1 14 1
  1 13 1
  1 16 1
PHASE8
#
```