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STOCK ASSESSMENT OF ALBACORE TUNA IN THE SOUTH PACIFIC OCEAN

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Executive Summary

This working paper presents the current stock assessment of albacore tuna (*Thunnus alalunga*) in the South Pacific Ocean. The assessment, like the previous assessment (Hoyle & Davies 2009), uses the integrated stock assessment model known as MULTIFAN-CL (or MFCL), under the assumption that there is a single stock of albacore tuna in the south Pacific ocean.

This assessment is an update of the previous assessment, and uses the same underlying structural assumptions as the 2009 assessment. Due to improved understanding of the data inputs, the model structure of the 2009 alternate case was applied in the 2011 reference case.

We offer the following conclusions, which are similar to those in 2009:

Stock status

- Estimated stock status is similar to 2009 estimates.
- Biological research indicates that male and female albacore have quite different growth curves, which are not included in the model. Growth curve errors can bias estimates of biomass and fishing mortality. Estimated management parameters should therefore be viewed with caution.
- 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.
- Estimates of $F_{2007\text{-}2009}/F_{MSY}$ and SB_{2009} / SB_{MSY} do not indicate overfishing above F_{MSY}, nor an overfished state below SB_{MSY}.
- Results from the 2009 assessment suggest that much variation in management parameters is attributable to steepness, which 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 less affected by uncertainty. They may also be more relevant to the management needs of the fishery.
- There is no indication that current levels of catch are causing recruitment overfishing, particularly given the age selectivity of the fisheries.
- Longline catch rates appear to be declining, and catches over the last 10 years have been at historically high levels. This CPUE trend may be significant for management.

A number of potential research directions are suggested.

- Change stock assessment structure to model different growth curves by sex, and incorporate other important factors that may be identified by biological research.
- Investigate alternative reference points that may be more relevant and more precise.
- Investigate the length frequency data in order to resolve the data conflicts that affect the model, and that may be biasing abundance estimates.
- Collaborate with scientists and industry from distant water fishing nations to better understand changes in fishing practices over time.
- Consider separating Chinese longliners from the 'Other' fisheries, due to increased catch.
- An integrated assessment of North and South Pacific albacore would be beneficial.
- Explore models with separate sub-populations by region.

- 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.

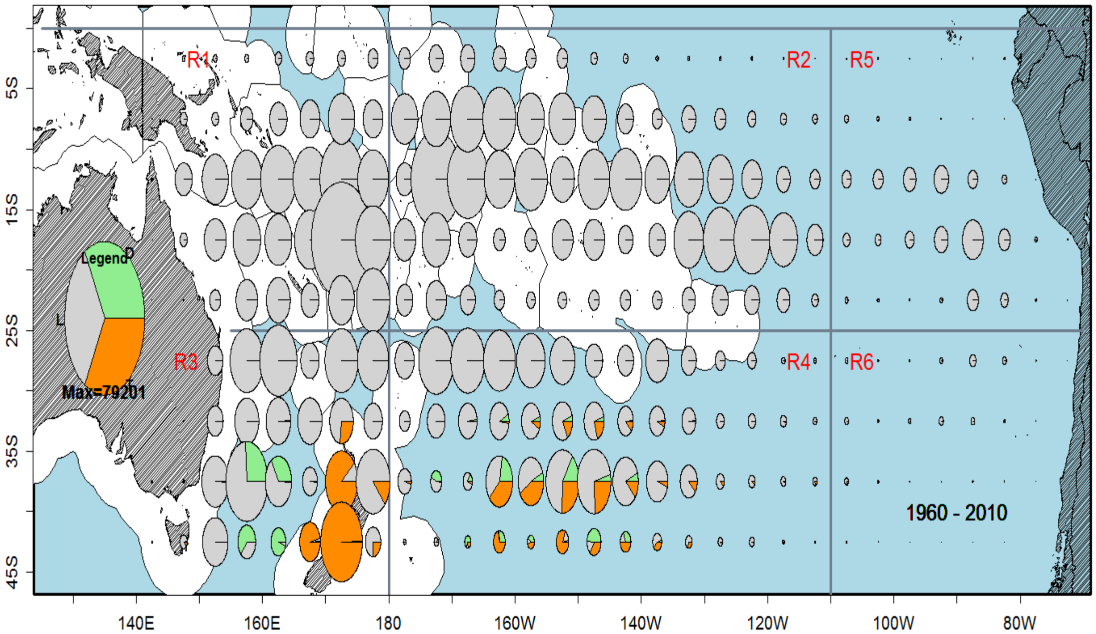

Figure 1: Map showing model regions 1 to 6, and the total catches (1960 to 2008) by 5° squares of latitude and longitude by the longline, troll, and driftnet fisheries.

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)* ($B_{2007-2009}/\tilde{B}_{MSY}$) and recent fishing mortality to fishing mortality at *MSY* ($F_{2007-2009}/\tilde{F}_{MSY}$). The methodology used for the assessment is commonly known as MULTIFAN-CL (or MFCL) (Fournier *et al.* 1998;Hampton & 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 & 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 & 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 & Clear 2008). Maximum recorded length is about 120 cm (FL). Analyses of new biological data (SPC-CSIRO unpublished data) suggest that males grow to a larger size than females.

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 (Figure 4). 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 50,000–70,000 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 was due to the development of small-scale longline fisheries in Pacific Island countries, and a recent increase is also apparent in the Chinese longline fishery (Figure 7). 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. In recent years catches have increased in Pacific Island Countries and Territories.

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 & Fournier 2001;Labelle & 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 & 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. First, the latitudinal boundary at 30°S was moved north to 25°S, after examining length-frequency data (Langley & 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 2009 and the current assessment maintain the same regional structure as in 2008, and used a single-model region, with the six spatial strata being used to define fisheries (**Figure 9**).

3.2 Temporal stratification

The time period covered by this assessment is July 1960 to June 2010. 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 2010 are very limited, so for most purposes, inferences should focus on results up to 2009.

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 fishery structure from 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 9.

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 were 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°-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 follow. Time-series of catches 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 1952–2009. 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 1975–2009, catch in numbers and effort by month and 5°-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°-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°-square resolution, have been provided by Chinese Taipei (1967–2010). 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, and 2004-2009 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°-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 & 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 11.

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°-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 1993–2010 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°-square resolution for the period 1986−2010. 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°-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 11), 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.

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 13). 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 14). 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 14). 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 13).

Another albacore tagging programme was started by SPC in January 2009 (Williams *et al.* 2009). Only a few tags have been returned so far, and the data from this tagging programme have not 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 15), 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. The combined effects of changing M and changing sex ratio at age results in a curved natural mortality ogive for the combined sexes.

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.

4.1.1 Total catch 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.

4.1.2 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.

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. For the 2008 assessment the divisors were changed to 20, giving a maximum effective sample size of 50.

For the 2009 assessment, divisors for most longline fisheries in the southern regions 3, 4, and 6 were set 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 the lengths 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 they were down-weighted with a divisor of 120 to avoid bias. 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 observed in the LF data for the Fijian and French Polynesian fleets, and a divisor of 40 was applied.

The current assessment used the same approach as was used in 2009.

4.1.3 Tagging data

A log-likelihood component for tagging data was computed using a Poisson distribution, as in assessments since 2005. 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 & 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 & 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.

4.4 Age and growth

Age and growth assumptions 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, apart from ages 2-5; and iii) the standard deviations in length-at-age is a linear function of the mean length-at-age.

The mean lengths of age-classes 2 to 5 are allowed to deviate from the von Bertalanffy growth curve. These deviations attract a small penalty to avoid over-fitting the size data.

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.

All longline fisheries were split into four by quarter, to accommodate strong seasonal variation in the length of fish caught (Langley & Hoyle 2008), which was noted in all regions.

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.

For the troll fisheries, selectivity 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 & Hampton 2005;Langley & Hampton 2006). MFCL does not have the facility to vary selectivity through time within a fishery, since it is constrained to be constant.

For the 2009 and the present 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 into period-specific fisheries in order to permit selectivity to change. Selectivity and catchability (which is confounded with selectivity) were estimated separately for each fishery period. 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 in Section 5.3.2. 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 & Hoyle 2008).

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. Time-varying catchability was applied to the New Zealand troll fisheries, because catch rates appear to be dominated by oceanography and availability, rather than by abundance (Adam Langley personal communication).

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. A sensitivity analysis to effort creep was not carried out for this assessment.

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).

Time varying penalties were applied to the effort deviations. For fisheries with standardized CPUE, penalties were adjusted to match the CV's estimated in the CPUE standardization (Bigelow & Hoyle 2009; Graham Pilling unpublished data). This resulted in more weight being given to the indices from regions 1 and 2, and the Korean and Chinese Taipei indices.

4.8 Natural mortality

Mean natural mortality (*M*) was fixed at 0.4 (Figure 15). *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 & 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).

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.

5 Results

This paper presents results based only on the reference case model, as developed in the previous assessment (Hoyle & Davies 2009). The results and diagnostics of this model are presented in detail, including yield estimates and performance indicators.

A 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 & 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 & Colgan 1992;Young & Hayes 2004). Finally, depletion of the more catchable individuals implies selection for low catchability, which may depress catch rates in the long term (Biro & Post 2008).

5.1 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 19) 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 16). 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 few 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 17). The model fit to tagging data for this version of the model is reasonably good, although tag return rates decline more quickly than expected.

- 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 18). 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. There is also significant short-term variability among samples (Figure 20), 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 21), and in plots of exploitable biomass versus observed CPUE (Figure 22). 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 22). 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.

5.2 Model parameter estimates

5.2.1 Catchability

Annual catchability for standardised fisheries was permitted to vary for the first period of the model, but held constant after any split (Figure 23). 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 23). 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.

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.

5.2.2 Selectivity

Selectivities for longline fisheries reveal some consistent seasonal patterns (Figure 24). 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.

5.2.3 Growth

The estimated growth curve is shown in Figure 25. 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 & 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 and/or sexes, 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. Preliminary results from research by SPC and CSIRO suggests that the average lengths of older fish differ quite significantly between sexes.

5.3 Stock assessment results

Results for the reference case model are presented .

5.3.1 Recruitment

There was evidence of trends in recruitment driving trends in biomass, with recruitments declining through the whole period (**Figure 26**). The declines in recruitment represent the model's attempt to fit a steeper decline in distant-water longline fisheries' CPUE than can be explained by the reported catch. Recent recruitment is estimated to be increasing, but is highly uncertain.

5.3.2 Biomass

Biomass is highly uncertain at the start of the 1960s, and depends on the assumptions made about the early steep decline in catch rates (Figure 27). In the 2009 assessment, scenarios that gave 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. Both the reference and the alternate case assume that CPUE before 1977 is independent of abundance. In the alternate case the early 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 in the reference case, 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 1975 is fairly consistent between the two models run this year and their equivalents in 2009. It is relatively stable until about 1990, and declines after this as total catches increase to twice their previous level.

In 2009 the lower biomass level estimated by models with down-weighted length frequency data was considered to be at least as likely as the higher level estimated by models that fit to both datasets. The overall level of biomass in the south Pacific albacore assessment tends to be 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 equivalent to assuming that both are true.

For these reasons the model with down-weighted length frequency data was preferred as the reference case for 2011.

Biomass and spawning biomass levels are estimated to be close to equilibrium unfished levels until about 1990 (Figure 28), due to above average recruitment early in the time series.

5.3.3 Fishing mortality

Fishing mortality (exploitation) rates for adult albacore are moderately low from the early 1970s to the mid-1990’s, and show a large increase since that time for adult fish (Figure 29). Estimated exploitation rates have increased since 2000 in response to higher catches (Figure 6 to Figure 8) 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 increasing, 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 0.25 for adults in the peak year 2010 (Figure 29), and averaging about 0.35 for fully recruited age classes (Figure 30). 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).

5.3.4 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 (2010) between about 35% and 80% of unfished levels (i.e. longline-vulnerable biomass has been reduced by between 20% and 65% due to the impact of fishing) (Table 7, Figure 32 and Figure 34). 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 proportion of the stock is available to the longline fishery, so increases in catch are likely to result in substantially more 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 in the seasons when larger fish are taken (Figure 32). The fishery’s impact on the exploitable biomass in the troll and driftnet fisheries has been negligible throughout the fishery’s history (Figure 32 and Figure 33).

Comparing the estimated impact of fishing on biomass (Figure 33) with the overall estimated biomass decline relative to initial biomass (Figure 34) demonstrates the degree to which the model is using recruitment to produce estimated biomass trends.

5.3.5 Yield analysis

Symbols used in the following discussion are defined in Table 6. Yield analyses conducted in this assessment incorporate the stock recruitment relationship (SRR) (Figure 35) into equilibrium biomass and yield computations. The assumed reference 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 2007–2009 average fishing mortality-at-age (*Fmult)* are shown in Figure 36.

The reference case results should be compared with results from the 2009 base case, rather than the median estimates of the 2009 grid. In 2009 all management parameters in 2009 used the median estimate from the grid, in order to take the distribution of the uncertainty into account. Results from the 2009 base case did not sit in the middle of the estimates from the uncertainty grid. The grid was not run this year.

Yield is maximised at Fmult = 3.8 for an MSY of 85,200 mt per year. This implies that the ratio $\mathrm{F}_{2007-2009}/\tilde{\mathrm{F}}_{\mathrm{MSY}}$ is approximately 0.26. The equilibrium biomass at MSY is estimated at 605,900 mt, approximately 53% of the equilibrium unexploited biomass. Spawning biomass (reproductive potential) at MSY (SB_{MSY}) is estimated to be 26% of the unfished level (SB_{MSY}/SB_0).

5.3.6 Stock assessment conclusions

Various quantities of potential management interest associated with the yield analyses are provided in Table 7. 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 $\mathrm{SB}_{2009}/\widetilde{\mathrm{SB}}_{\mathrm{MSY}}$, $\mathrm{B}_{2007-2009}/\tilde{\mathrm{B}}_{\mathrm{MSY}}$, and $\mathrm{F}_{2007-2009}/\tilde{\mathrm{F}}_{\mathrm{MSY}}$ 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. Category ii ratios are more robust than those in category i.

The ratios $B_{2007-2009}/B_{2007-2009,F=0}$ and $SB_{2009}/SB_{2009,F=0}$ 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 0.63 (i.e. spawning biomass reduced by 37% due to the impact of fishing). These represent a moderate level of depletion, above the equivalent equilibrium-based limit reference points B_{MSY}/B_0 = 0.53 and SB_{MSY}/SB_0 = 0.26).

Other reference points useful in indicating the current stock status are $\tilde{\mathrm{B}}_{\mathrm{F}_{2007-2009}}/\tilde{\mathrm{B}}_{\mathrm{MSY}}$ (1.49) and $\widetilde{\mathrm{SB}}_{\mathrm{F}_{2009}}/\widetilde{\mathrm{SB}}_{\mathrm{MSY}}$ (2.41). Together with the yield-based reference point $\mathrm{Y}_{\mathrm{F}_{2007-2009}}/\mathrm{MSY}$ (0.67), 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 $F_{2007-2009}/\tilde{F}_{MSY}$ (0.26), $SB_{2009}/\widetilde{SB}_{MSY}$ (2.25), and $B_{2007-2009}/\tilde{B}_{MSY}$ (1.26) do not indicate that overfishing of South Pacific albacore is occurring, nor do they indicate that the stock is in an overfished state.

Time series of ratios of $F_t/\tilde{F}_{MSY}$, $B_t/\tilde{B}_{MSY}$, and $SB_t/\widetilde{SB}_{MSY}$ (Figure 37 and Figure 38) 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 close to B_{MSY}. B_{2009} is estimated to be close to B_{MSY}.

6 Discussion and conclusions

The current stock assessment was carried out by rerunning several models from the 2009 south Pacific albacore assessment (Hoyle & Davies 2009), with no changes to the model structure. It follows significant structural changes from the 2005, 2006, and 2008 assessments (Langley & Hampton 2005;Langley & Hampton 2006;Hoyle *et al.* 2008a), which themselves made large changes from previous assessments (Hampton 2002;Labelle & Hampton 2003).

Cluster analyses, inclusion of additional data, and close examination of the effects of targeting have resulted in a more reliable CPUE series (Bigelow & Hoyle 2009; Graham Pilling unpublished data) than the one used in the 2008 assessment (Bigelow & Hoyle 2008), or the un-standardized data used before 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.

Patterns of length frequency variation are broadly consistent with the changes in catches (Bromhead *et al.* 2009). 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 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.

Some conflict remains between length frequency and CPUE 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, results in estimates with lower biomass and higher, but still moderate, fishing pressure (Hoyle & Davies 2009), and allows 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.

Recent biological work (SPC-CSIRO unpublished data) suggests that the males ultimately grow to considerably larger sizes than females. This new finding is very significant for the stock assessment, since the model is strongly influenced by estimates of asymptotic length. The current assessment does not take this information into account, and this lack of fit may help to explain the difficulty we have reconciling the CPUE data with the length frequency data.

Growth curve errors can considerably bias estimates of biomass and fishing mortality. This suggests that yield estimates from the model should be viewed with caution. Trends in CPUE may be more informative.

6.1 Biomass trends

Two major features are evident in CPUE data: the steep decline between 1960 and 1975, and the 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. The decline is steeper than can be accounted for by fishing pressure alone, even though total catch increases considerably over this period, so the model uses recruitment to lower the exploitable biomass. It seems likely that recruitment did not actually decline but that biomass estimates are elevated by the data conflict between length and CPUE data discussed above. Growth curve errors can considerably bias estimates of biomass and fishing mortality. At lower biomass levels, the increased catch since 1990 would be sufficient to account for the observed CPUE decline.

6.2 Sensitivity analyses

No sensitivity analyses were carried out for this assessment, but the results of sensitivity analyses undertaken for the 2009 assessment should be considered when viewing the current results. For example, 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. In 2009, 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, and in 2009 it ranged 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 2009 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 under-estimated the true uncertainty of the model, since parameter uncertainty was not included, and many assumptions were not included (e.g. regarding relatively constant q and selectivity, variation of natural mortality with age).

6.3 Management implications

Estimates of fishery impacts on biomass ($B_{current}/B_{current,F=0}$) progressively increased between the 2003 assessment (3%), the 2005 (9%), 2006 (10%), and 2008 assessments (30%), as model configurations progressively changed. In the 2009 assessment the impact on biomass declined to a median estimate of 20% (or 17% in the base case) and in the current assessment it is 20%. Correspondingly, the *MSY* estimate from this assessment is close to the 2009 estimate (85,200 mt versus 81,600 mt (median estimate), 64,000 mt, 181,000 mt, 183,000 mt, and 300,000 mt in the previous 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). Movement rates into and out of EEZ's may be lower than peak catch levels, and there may be 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 observations support 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 recent increase in catch has been paralleled by a reduction in CPUE, which together with increasing fuel prices has affected the economics of the albacore fishery.

The current assessment estimates moderate levels of exploitation ($B_{2007-2009}/B_{2007-2009,F=0}$ = 0.80, and $F_{2007-2009}/\tilde{F}_{MSY}$ = 0.26). Nevertheless, given both the impacts of exploitation and the estimated decline in recruitment, the biomass of that portion of the stock vulnerable to the longline fishery is estimated to be somewhat reduced. The contributions of each impact are uncertain and the totals vary among fisheries. The current level of impact is estimated at between about 20% and 65%, depending on the fishery, having increased sharply in recent years. The impact on the spawning biomass component of the stock is approximately 41%.

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 57,130 mt; *MSY* 85,200 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.

The 2011 stock assessment has rerun 2 models from the 2009 assessment. Future assessments will require improvement to the structure, taking account of new information about sex differences in growth rates. 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 indicators based on something other than MSY.

6.4 Conclusions and recommendations

Stock status

- Estimated stock status is similar to 2009 estimates.
- Biological research indicates that male and female albacore have quite different growth curves, which are not included in the model. Growth curve errors can bias estimates of biomass and fishing mortality. Estimated management parameters should therefore be viewed with caution.
- 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.
- Estimates of $F_{2007\text{-}2009}/F_{MSY}$ and SB_{2009} / SB_{MSY} do not indicate overfishing above F_{MSY}, nor an overfished state below SB_{MSY}.
- Results from the 2009 assessment suggest that much variation in management parameters is attributable to steepness, which 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 less affected by uncertainty. They may also be more relevant to the management needs of the fishery.
- There is no indication that current levels of catch are causing recruitment overfishing, particularly given the age selectivity of the fisheries.
- Longline catch rates appear to be declining, and catches over the last 10 years have been at historically high levels. This CPUE trend may be significant for management.

Recommended model developments

- Change stock assessment structure to model different growth curves by sex, and other important factors that may be identified by biological research.
- Investigate alternative reference points, such as reference points based on expected catch rates, which may be more relevant and more precise.
- Investigate the length frequency data in order to resolve the data conflicts that affect the model, and may be biasing abundance estimates.
- Collaborate with scientists and industry from distant water fishing nations to better understand changes in fishing practices over time.

- 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.
- Consider separating Chinese longliners from the 'Other' fisheries.
- 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.
- Explore models with separate sub-populations by region.

Related research

- Continue 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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9 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. In the final stage of the run the ESS divisor was changed to 500 for all fisheries, and estimation switched off for all growth parameters.
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: Details of objective function components.

Objective function component	
Number of parameters	6487
Total catch log-likelihood	96.6
Length frequency log-likelihood	-144797.8
Tag log-likelihood	444.0
Effort dev penalty	1756.2
Penalties	2079.1
Total function value	-142164.0
Maximum gradient at termination	0.0009

Table 5: Contributions to the log-likelihood by length-frequency data of each fishery.

Method	Region	Flag	1	2	3	4	ALL
1	AU	L	-182	-384	-143	-72	-781
	FJ	L	-1,350	-1,805	-1,910	-1,407	-6,472
	JP	L	-1,752	-1,045	-3,378	-2,065	-8,239
	KR	L	-671	-1,434	-1,212	-793	-4,111
	NC	L	-2,098	-2,532	-2,588	-2,435	-9,652
	OT	L	-1,017	-1,723	-1,613	-745	-5,097
	TW	L	-2,453	-1,868	-1,901	-1,800	-8,021
2	AS,WS	L	-1,516	-1,570	-1,505	-1,378	-5,969
	JP	L	-726	-2,302	-1,742	-2,517	-7,287
	KR	L	-2,333	-1,782	-2,048	-2,481	-8,644
	OT	L	-1,283	-1,520	-1,718	-1,142	-5,662
	PF	L	-1,743	-1,344	-1,454	-1,872	-6,414
	TO	L	-1,541	-1,915	-1,787	-1,939	-7,181
	TW	L	-2,629	-1,532	-1,819	-2,612	-8,592
3	AU	L	-282	-974	-950	-579	-2,786
	JP	L	-83	-3,302	-3,110	74	-6,422
	KR	L	-84	-815	-620	-277	-1,796
	NZ	L	-1,151	-1,498	-830	-488	-3,966
	OT	L	-210	-575	-979	-397	-2,162
	TW	L	-44	-718	-1,706	-116	-2,584
4	JP	L	-139	-968	-634	-274	-2,016
	KR	L	-297	-1,741	-1,111	-43	-3,193
	OT	L	-454	-736	-1,127	-406	-2,722
	TW	L	-732	-2,358	-2,374	-138	-5,604
5	JP	L	29	32	-1,596	190	-1,344
6	JP	L	-344	-1,033	-1,298	-1,064	-3,739
3	ALL	D					-612
4	ALL	D					-304
3	ALL	T					-7,804
4	ALL	T					-5,624
			-25,085	-37,442	-41,151	-26,776	-144,798

Table 6: Descriptions of symbols used in the yield analysis.

Symbol	Description
$F_{2007\text{-}2009}$	Average fishing mortality-at-age for 2007–2009
F_{MSY}	Fishing mortality-at-age producing the maximum sustainable yield (*MSY*)
$\tilde{Y}_{F_{2007-2009}}$	Equilibrium yield at $F_{2005-2007}$
MSY	Equilibrium yield at F_{MSY}, or maximum sustainable yield
$\tilde{B}_0$	Equilibrium unexploited total biomass
$\tilde{B}_{F_{2007-2009}}$	Equilibrium total biomass at $F_{2005-2007}$
$\tilde{B}_{MSY}$	Equilibrium total biomass at MSY
$\tilde{SB}_0$	Equilibrium unexploited adult biomass
$SB_{F_{2009}}$	Equilibrium adult biomass at $F_{2005-2007}$
$\tilde{SB}_{MSY}$	Equilibrium adult biomass at MSY
$B_{2007-2009}$	Average current (2007–2009) total biomass
SB_{2009}	Average current (2007–2009) adult biomass
$SB_{2007-2009,F=0}$	Average current (2007–2009) total biomass in the absence of fishing.

Table 7: Management parameters estimated from the 2011 Reference case model, and estimates from the 2009 assessment, for comparison.

Management quantity	Reference case		2009 Base case	2009 Median
$C_{2007\text{-}2009}$	54,520	$C_{2005\text{-}2007}$	66,869	65,801
$YF_{2007\text{-}2009}$	57,130	$YF_{2005\text{-}2007}$	64,490	58,955
MSY	85,200	MSY	97,610	81,580
$YF_{2007\text{-}2009} / MSY$	0.67	$YF_{2005\text{-}2007} / MSY$	0.66	0.72
$C_{2007\text{-}2009} / MSY$	0.64	$C_{2005\text{-}2007} / MSY$	0.69	0.80
F_{MSY}	0.14	F_{MSY}	0.14	0.16
$F_{2007\text{-}2009} / F_{MSY}$	0.26	$F_{2005\text{-}2007} / F_{MSY}$	0.25	0.29
B_0	1,141,000	B_0	1,309,000	1,098,500
B_{MSY}	605,900	B_{MSY}	692,100	553,200
B_{MSY} / B_0	0.53	B_{MSY} / B_0	0.53	0.49
$B_{2007\text{-}2009}$	762,240	$B_{2005\text{-}2007}$	965,860	863,665
$BF_{2007\text{-}2009}$	903,500	$BF_{2005\text{-}2007}$	1,041,000	836,300
$B_{2007\text{-}2009}F_0$	950,947	$B_{2005\text{-}2007}F_0$	1,159,433	1,084,933
SB_0	400,700	SB_0	460,400	406,600
SB_{MSY}	104,200	SB_{MSY}	120,000	101,700
SB_{MSY} / SB_0	0.26	SB_{MSY} / SB_0	0.26	0.24
SB_{2009}	234,537	SB_{2007}	273,557	236,793
SBF_{2009}	251,500	SBF_{2007}	292,500	235,250
$SB_{2009}F_0$	372,043	$SB_{2007}F_0$	402,873	390,193
$B_{2007\text{-}2009} / B_0$	0.67	$B_{2005\text{-}2007} / B_0$	0.74	0.76
$BF_{2007\text{-}2009} / B_0$	0.79	$BF_{2005\text{-}2007} / B_0$	0.80	0.74
$B_{2007\text{-}2009} / B_{MSY}$	1.26	$B_{2005\text{-}2007} / B_{MSY}$	1.40	1.53
$BF_{2007\text{-}2009} / B_{MSY}$	1.49	$BF_{2005\text{-}2007} / B_{MSY}$	1.50	1.49
$B_{2007\text{-}2009} / B_{2007\text{-}2009}F_0$	0.80	$B_{2005\text{-}2007} / B_{2005\text{-}2007}F_0$	0.83	0.80
SB_{2009} / SB_0	0.59	SB_{2007} / SB_0	0.59	0.60
SBF_{2009} / SB_0	0.63	SBF_{2007} / SB_0	0.64	0.59
SB_{2009} / SB_{MSY}	2.25	SB_{2007} / SB_{MSY}	2.28	2.44
SBF_{2009} / SB_{MSY}	2.41	SBF_{2007} / SB_{MSY}	2.44	2.36
$SB_{2009} / SB_{2009}F_0$	0.63	$SB_{2007} / SB_{2007}F_0$	0.68	0.64

10 Figures

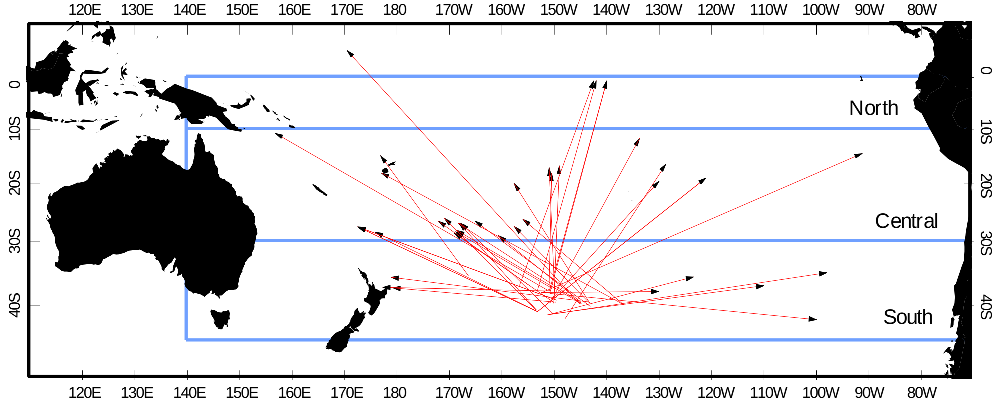

Figure 2: Movements of tagged South Pacific albacore (from Labelle and Hampton 2003).

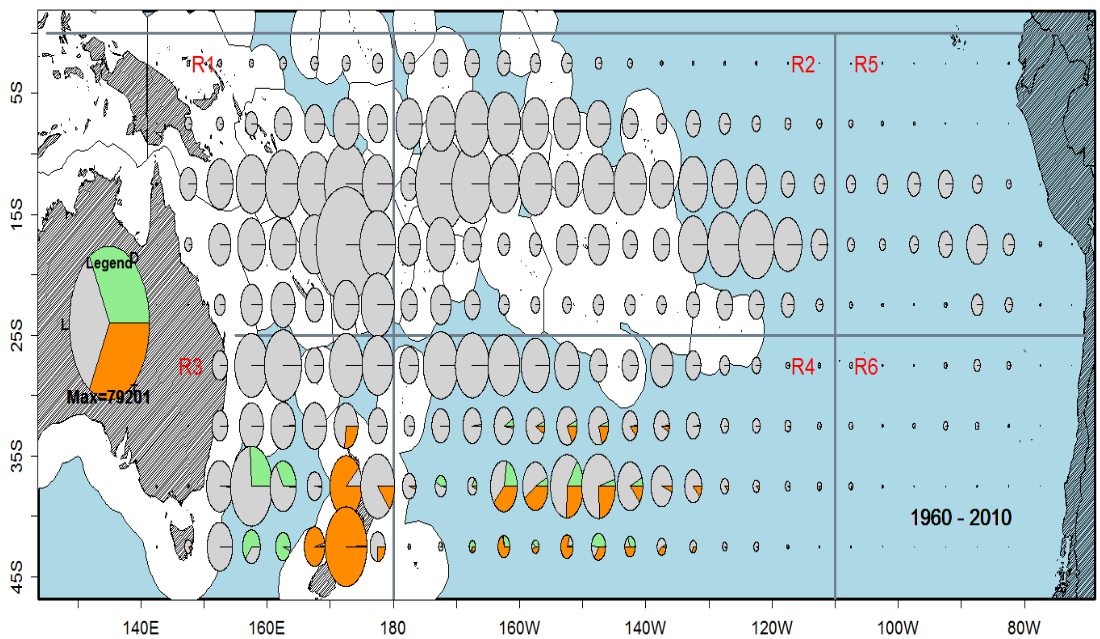

Figure 3: Map showing model regions 1 to 6, and the total catches (1960 to 2010) by 5° squares of latitude and longitude by the longline, troll, and driftnet fisheries.

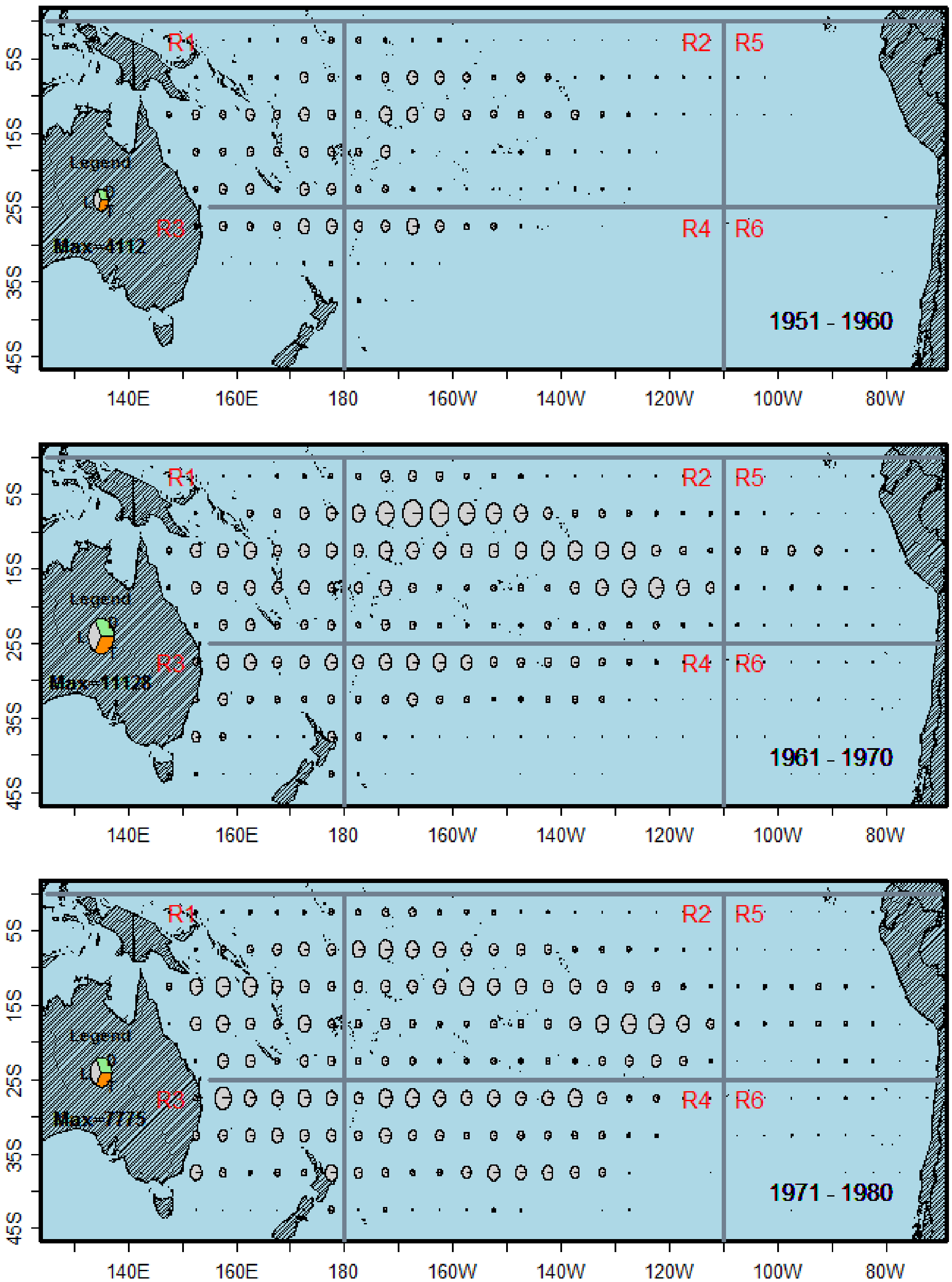

Figure 4a: Total catch by decade by 5°-squares of latitude and longitude by fishing gear: longline (L), driftnet (G), and troll (T). The area of the pie chart is proportional to the total catch. The boundary of the stock assessment area is delineated by the black line and regional boundaries are delineated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

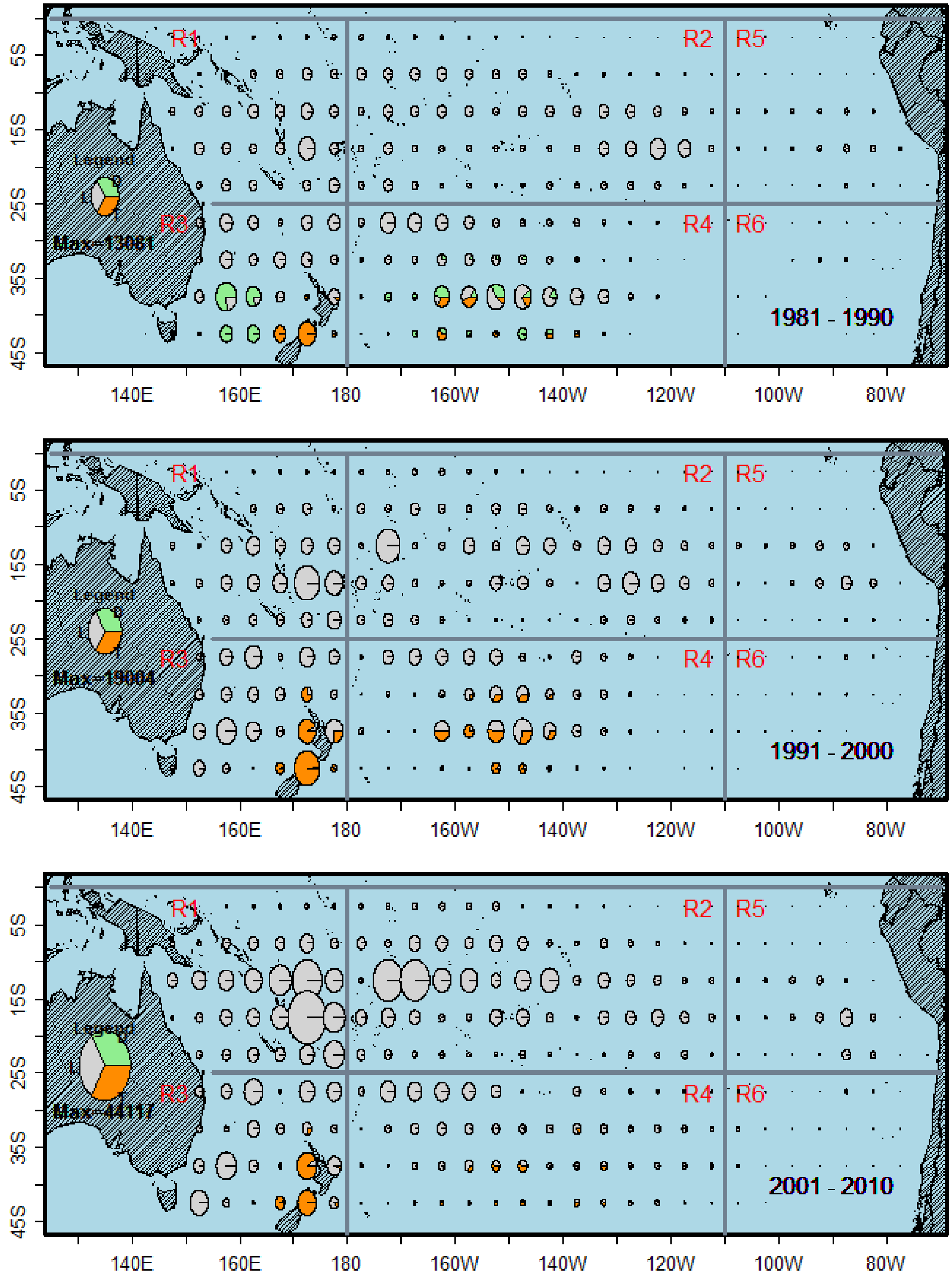

Figure 4b: Total catch by decade by 5°-squares of latitude and longitude by fishing gear: longline (L), driftnet (G), and troll (T). The area of the pie chart is proportional to the total catch. The boundary of the stock assessment area is delineated by the black line and regional boundaries are delineated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

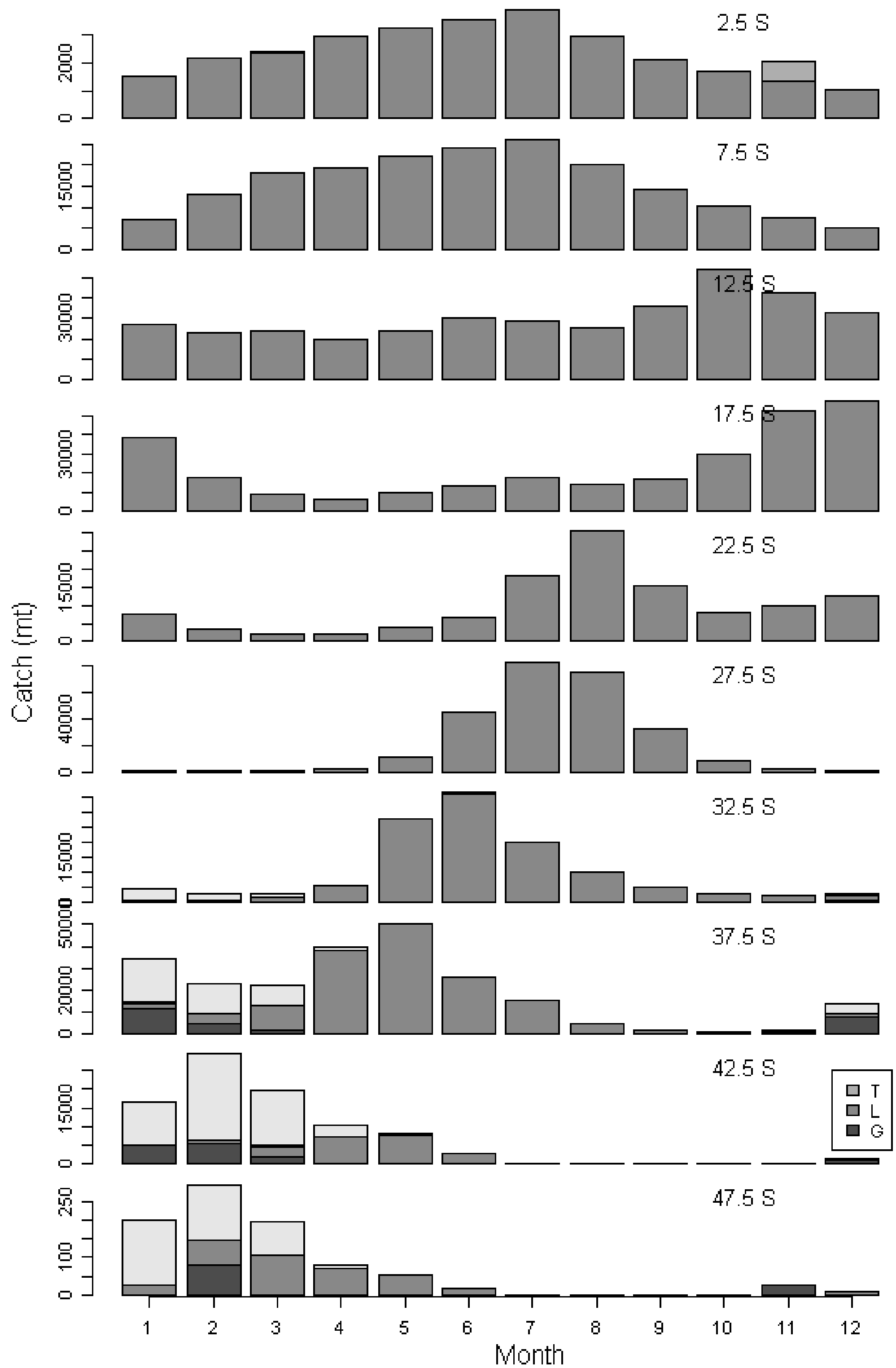

Figure 5: Cumulative monthly distribution of South Pacific albacore catch by gear (T=troll, L= longline, G=drift net) by 5° latitudinal band for 1980 to 2003 combined.

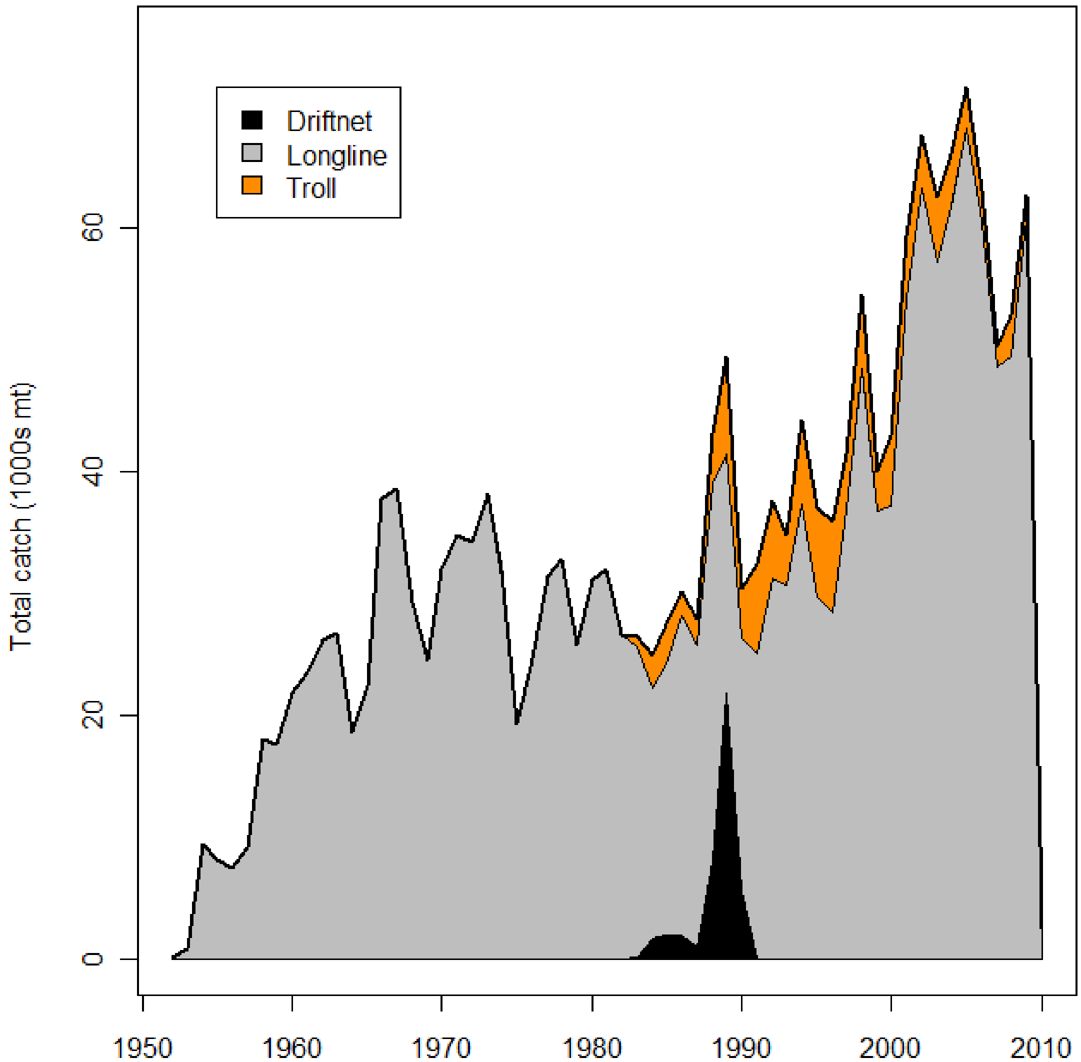

Figure 6: Total annual catch (mt) of South Pacific albacore by fishing method for 1952 to 2010.

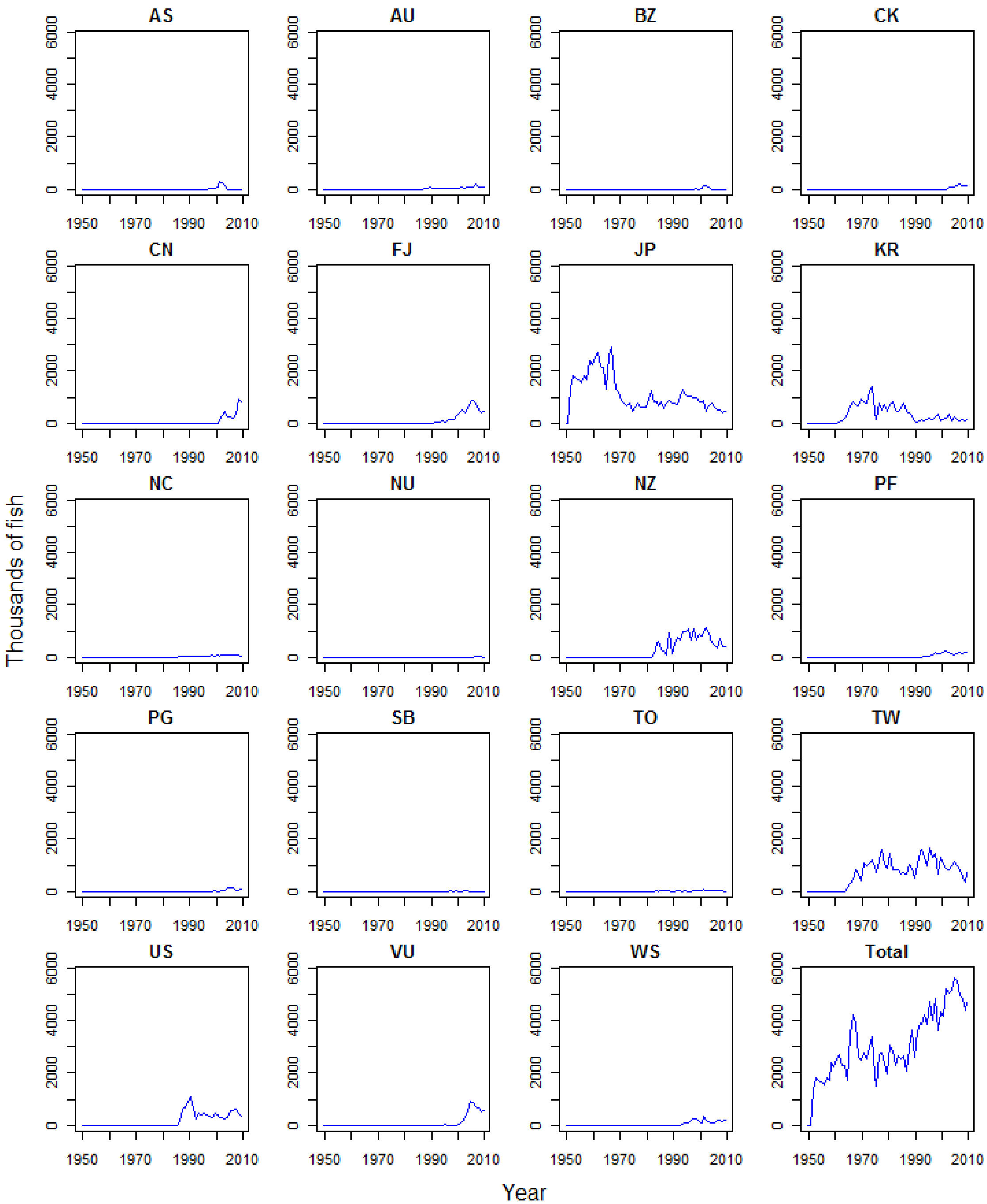

Figure 7: Annual catches by flag for the flags with the most cumulative catch (catches in thousands of fish). Driftnet catches are not included.

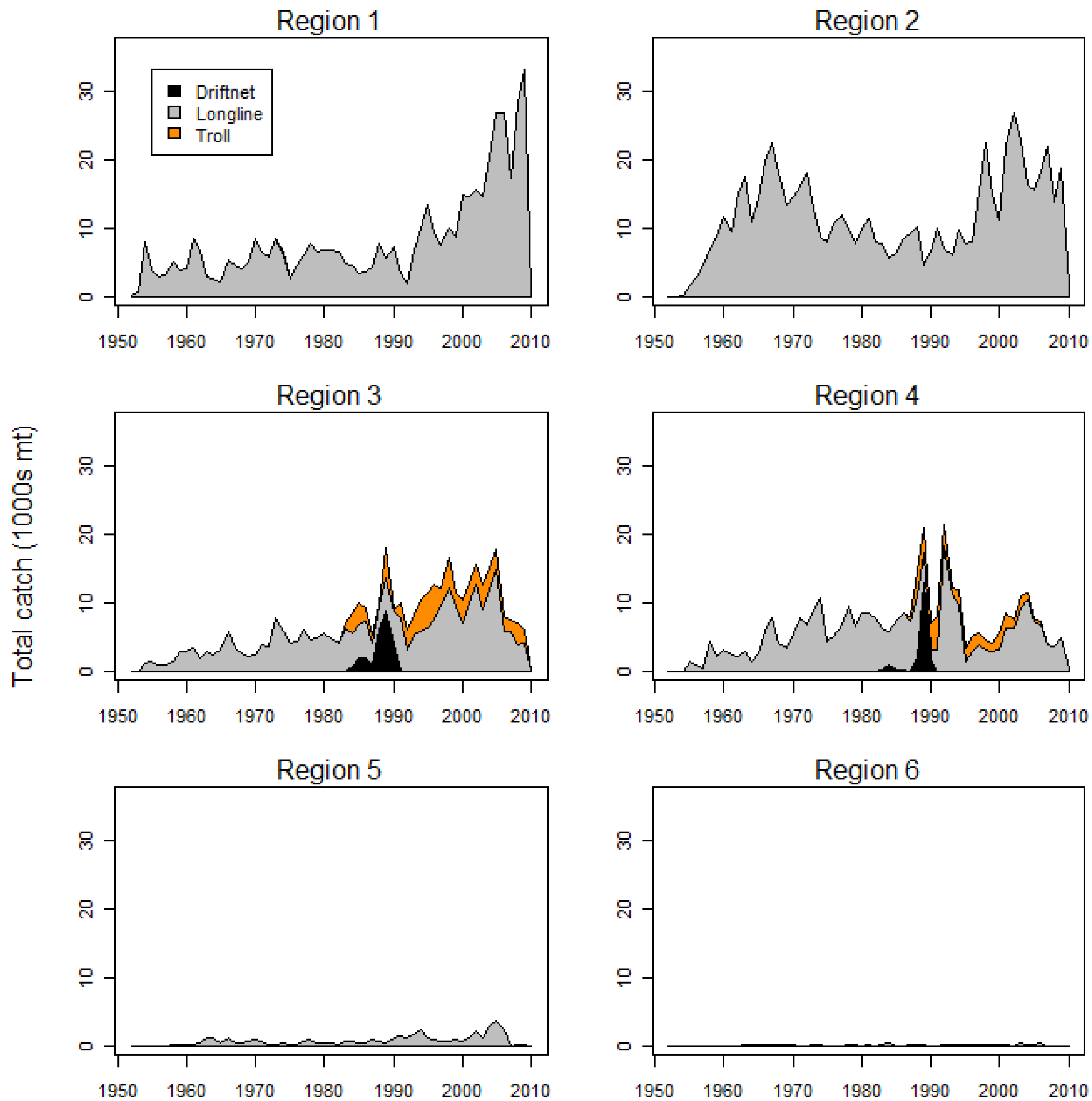

Figure 8: Total annual catch (mt) of South Pacific albacore by fishing method and region for 1952 to 2010.

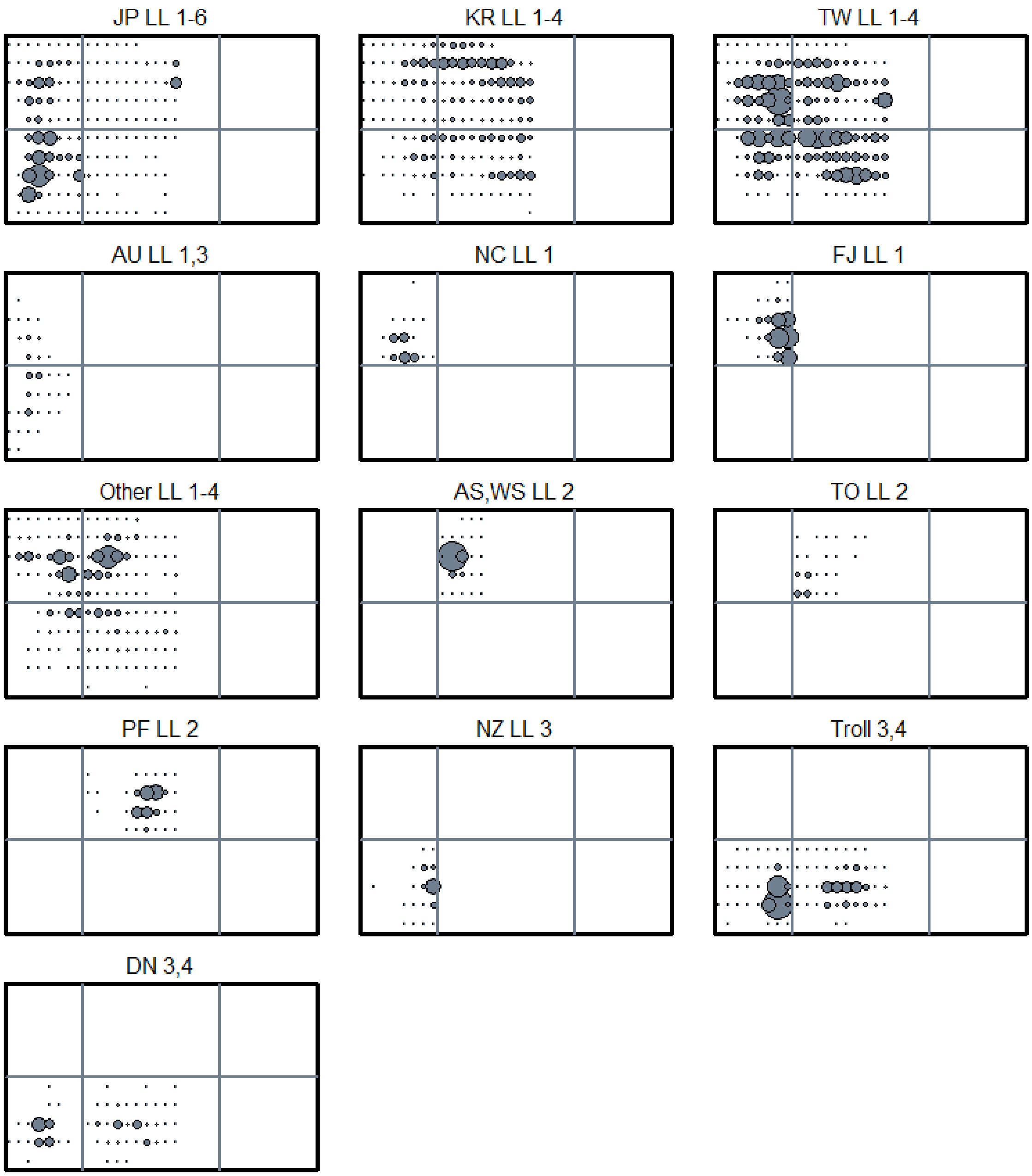

Figure 9: Cumulative albacore catch by fishery by 5°-square of latitude and longitude from 1970 to 2010. The circle size is proportional to the cumulative catch (maximum circle size corresponds to 41,000 mt). Grey lines represent regional boundaries.

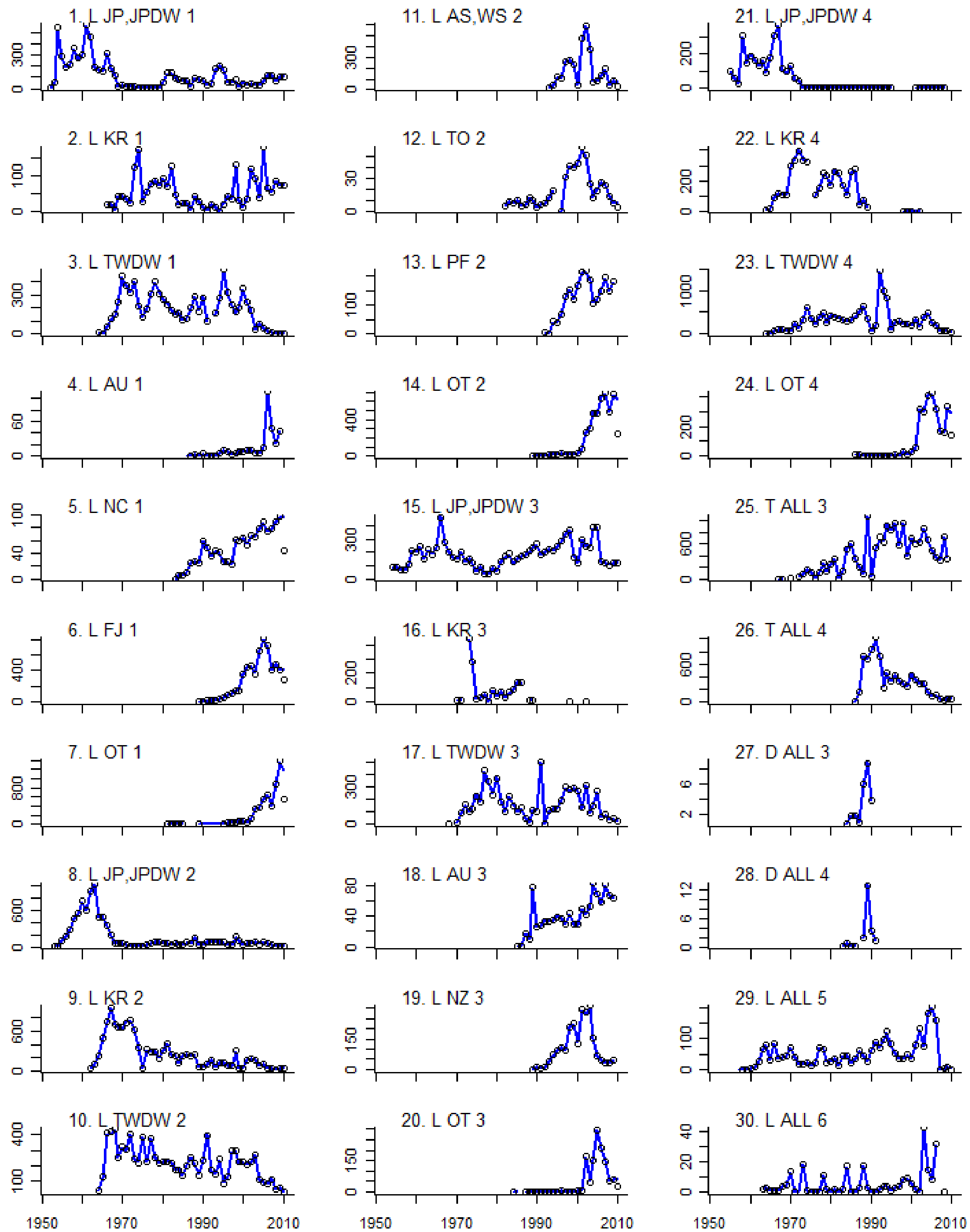

Figure 10: Annual catches (observed) by fishery (catches in thousands of fish for all fisheries except driftnet).

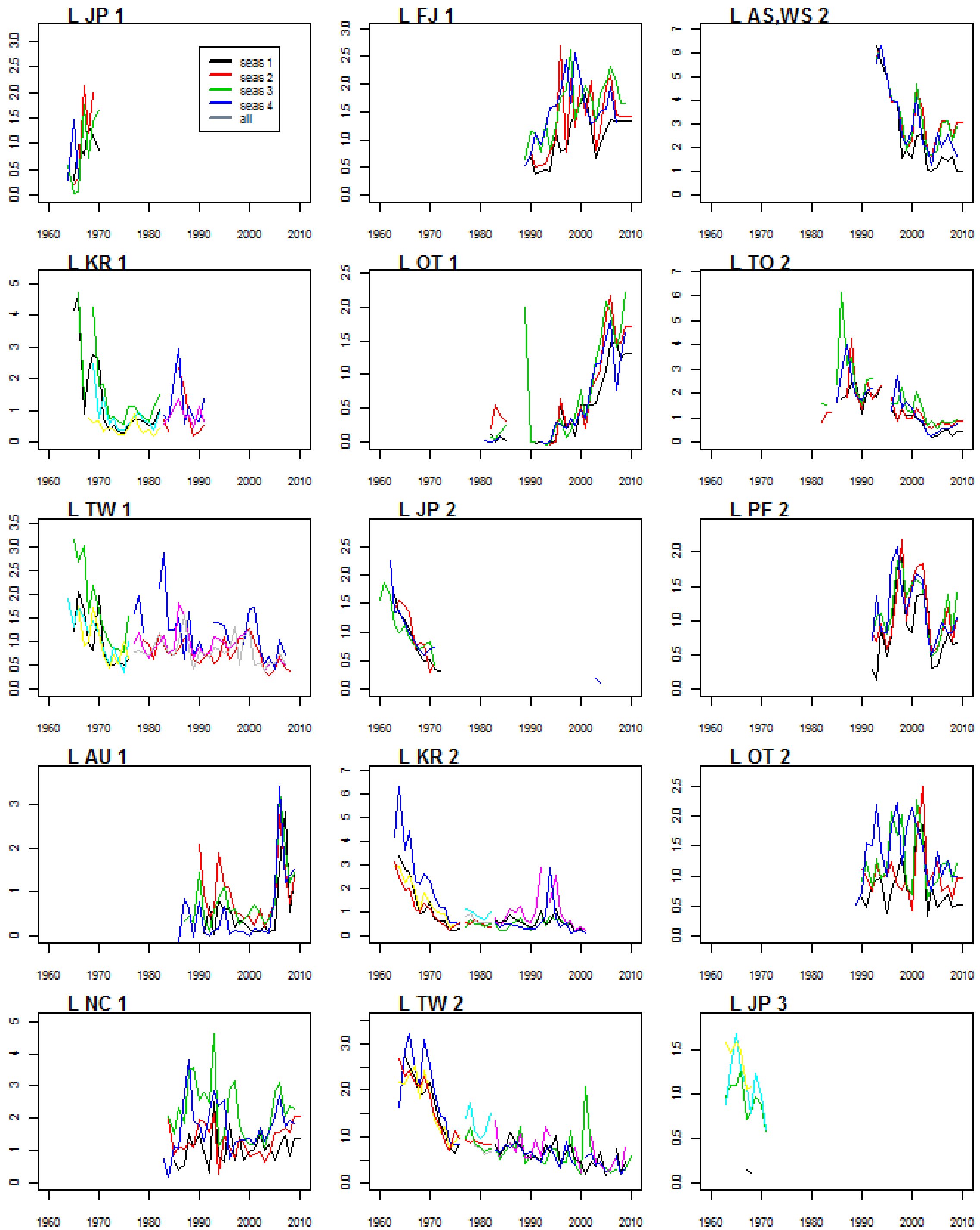

Figure 11a: Annual average catch rates by fishery. Catch rates for standardised fisheries (all JP, KR, and TW) have no units. Non-standardised longline fisheries are expressed as number per 100 hooks; troll are expressed as number per vessel·days fished; drift net are expressed as mt per day.

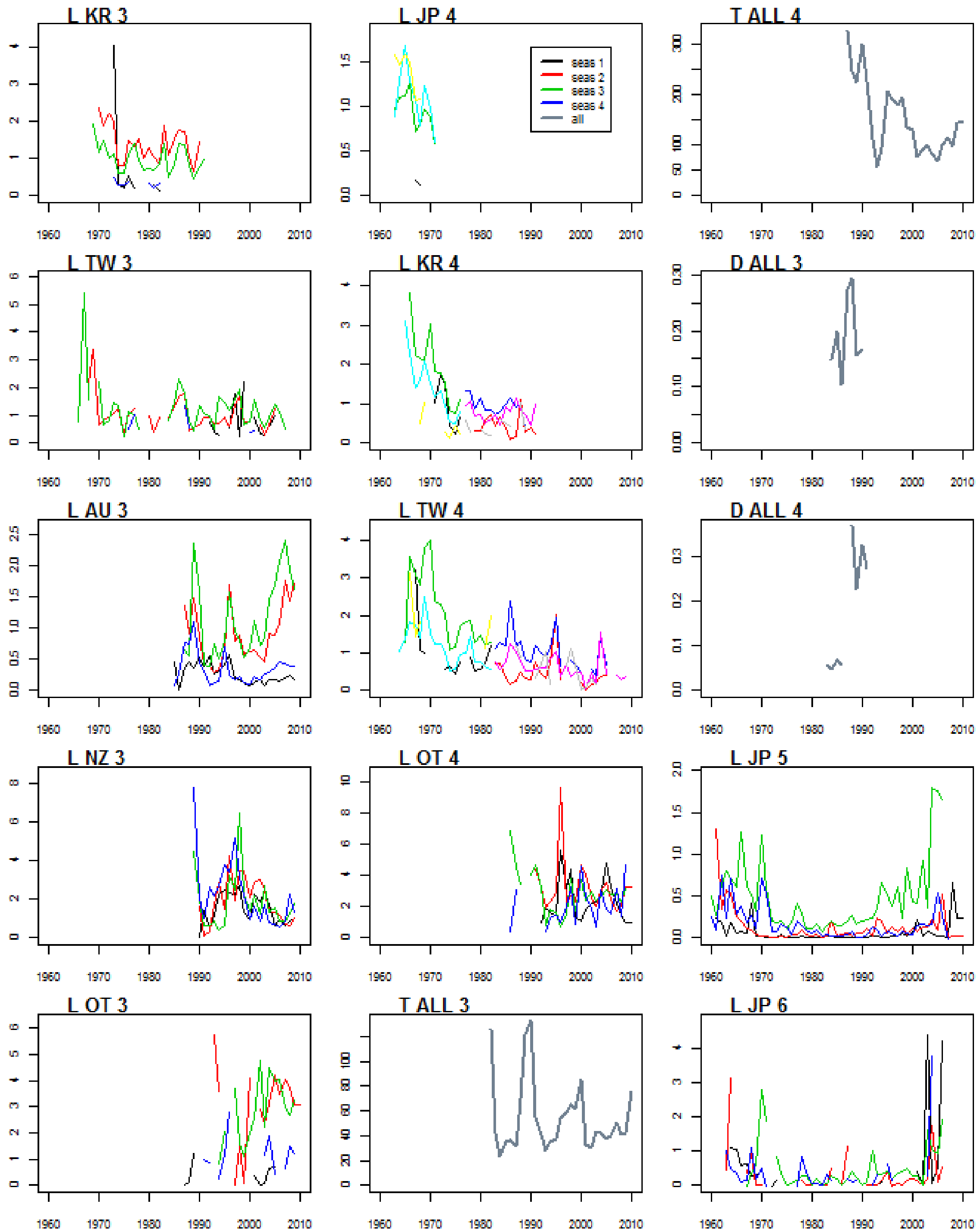

Figure 10b: Annual average catch rates by fishery. Catch rates for standardised fisheries (all JP, KR, and TW) have no units. Non-standardised longline fisheries are expressed as number per 100 hooks; troll are expressed as number per vessel·days fished; drift net are expressed as mt per day.

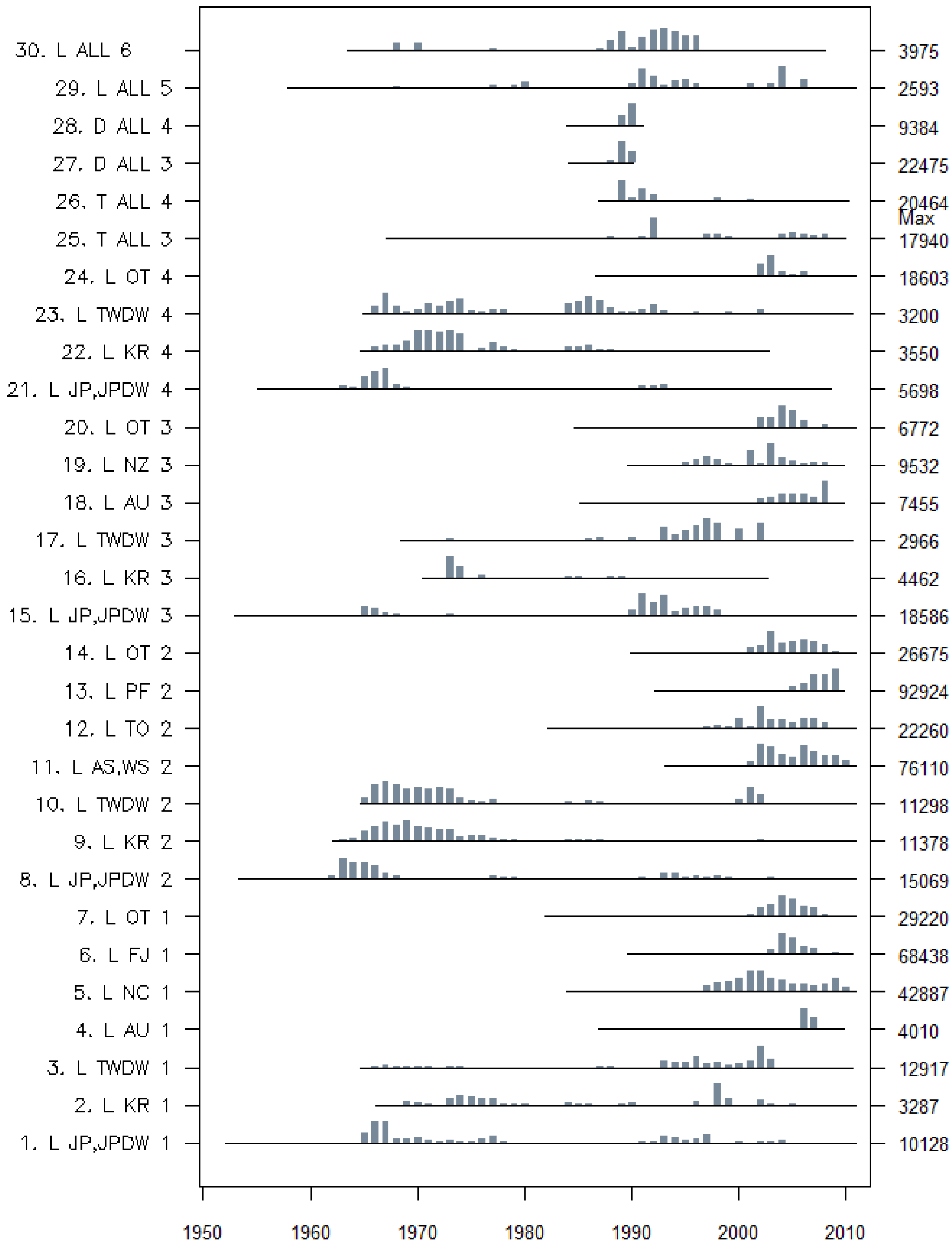

Figure 12: Length-frequency samples by fishery and year. The number on the y-axis represents the maximum number of fish measured in a single year for the fishery. Frequency histograms are scaled relative to the maximum value for the fishery. The length of the x-axis denotes the period of catch and effort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

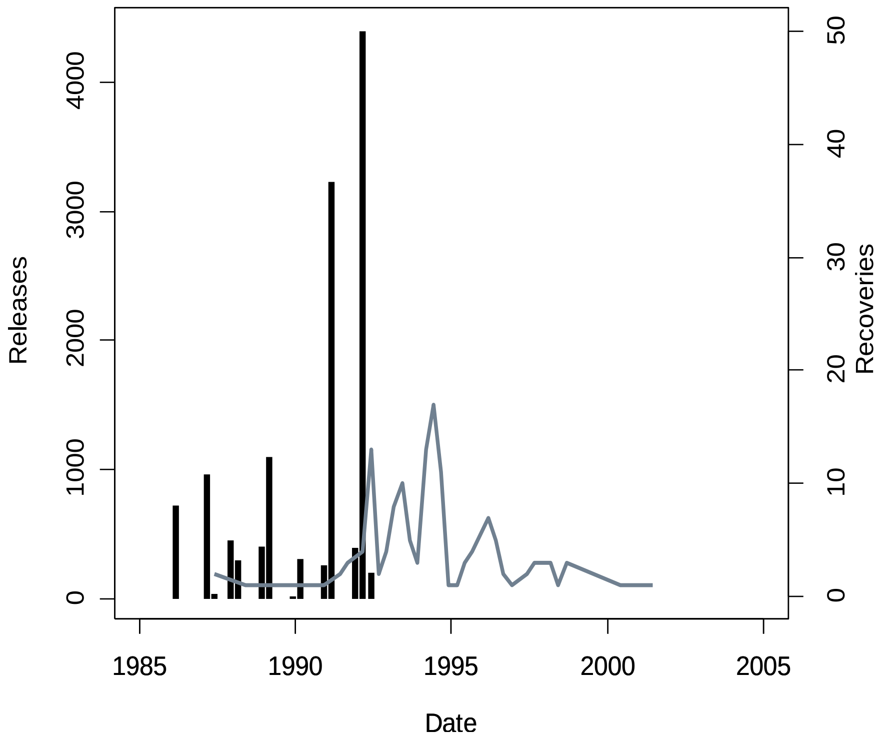

Figure 13: Tag releases (bars) and recoveries (line) by quarter for the South Pacific albacore fishery.

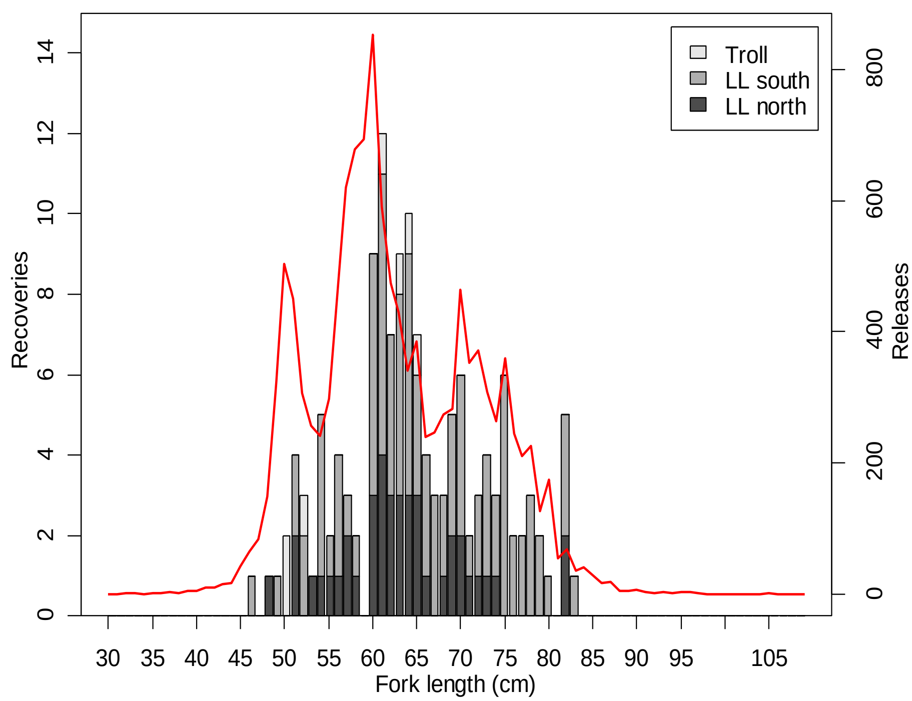

Figure 14: Total number of released tagged albacore (red line) and recoveries (bar plot) by length class. Recoveries are aggregated by groups of fisheries; northern and southern longline fisheries and troll fisheries.

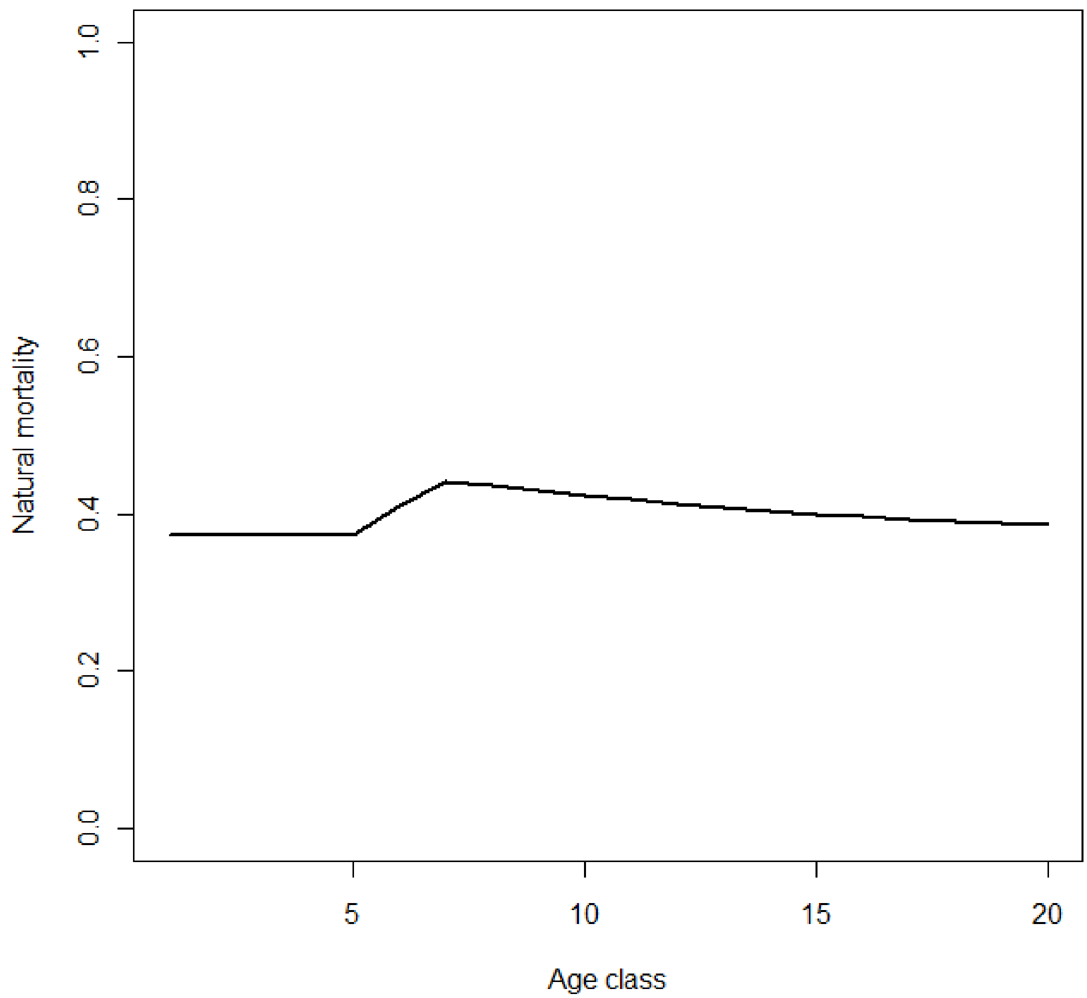

Figure 15: Natural mortality at age.

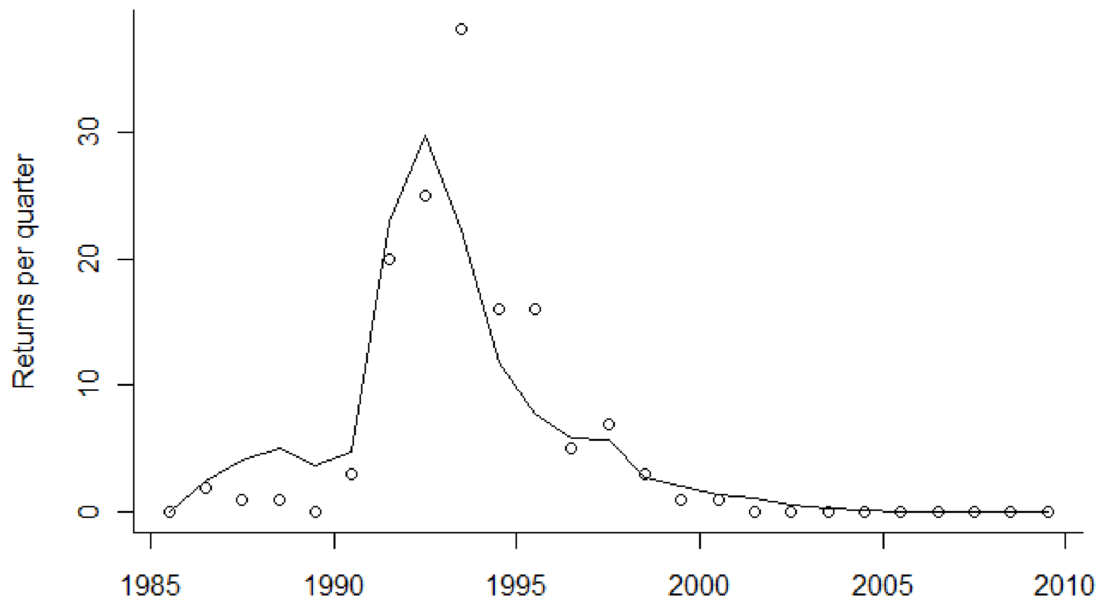

Figure 16: A comparison of observed (points) and predicted (line) number of tag returns per quarter from the South Pacific albacore fishery.

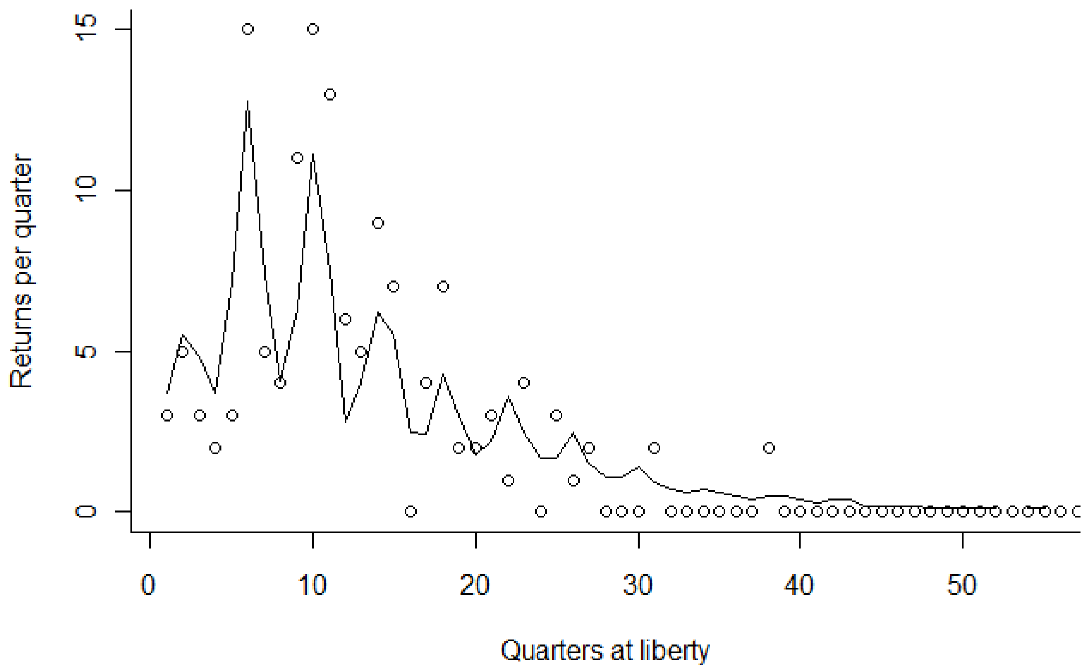

Figure 17: A comparison of observed (points) and predicted (line) number of tag returns by period at liberty (quarters) from the South Pacific albacore fishery.

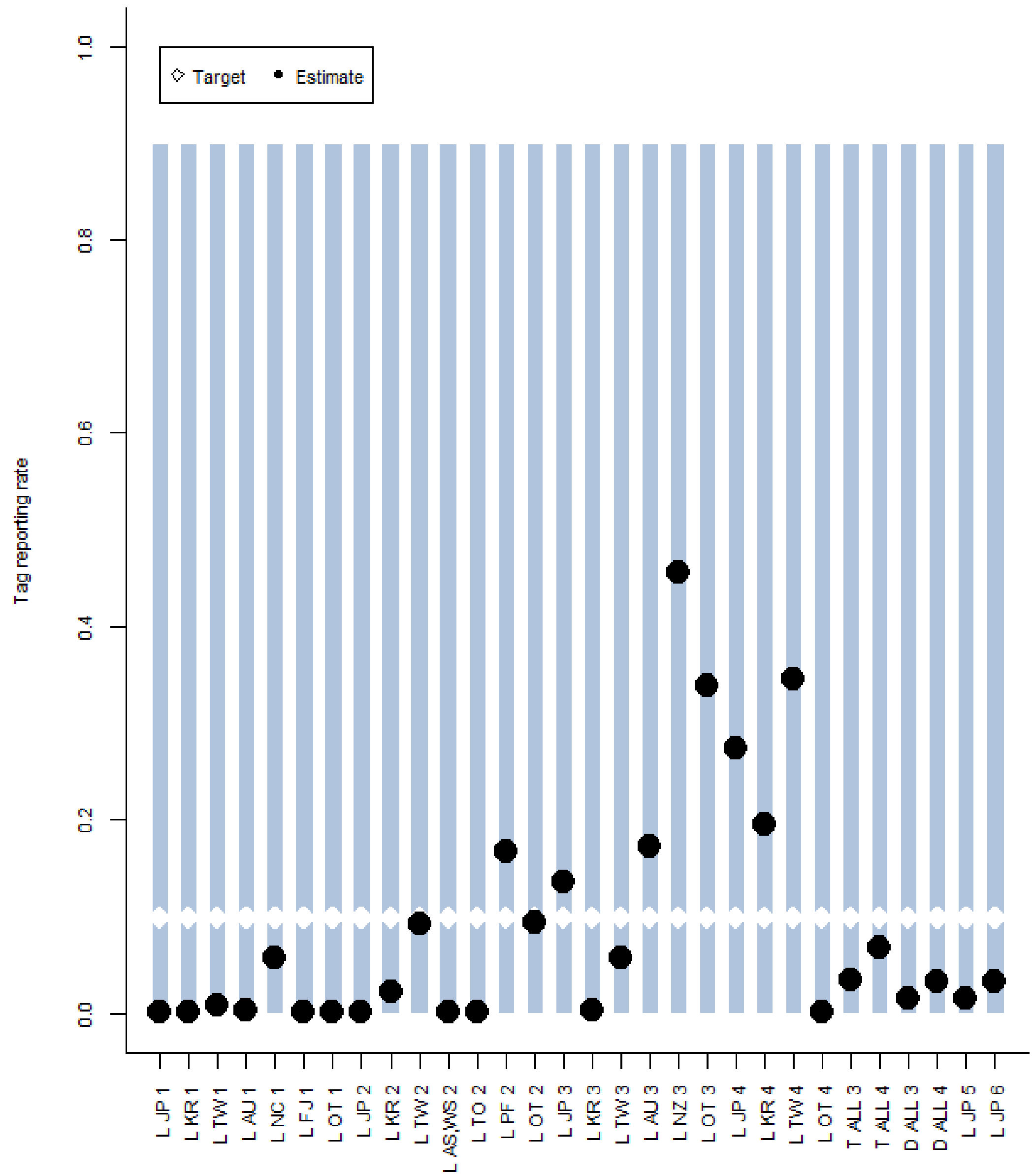

Figure 18: Estimated tag-reporting rates by fishery (black circles). White diamonds indicate the modes of the priors for each reporting rate, and grey bars indicate a range of ±1 SD.

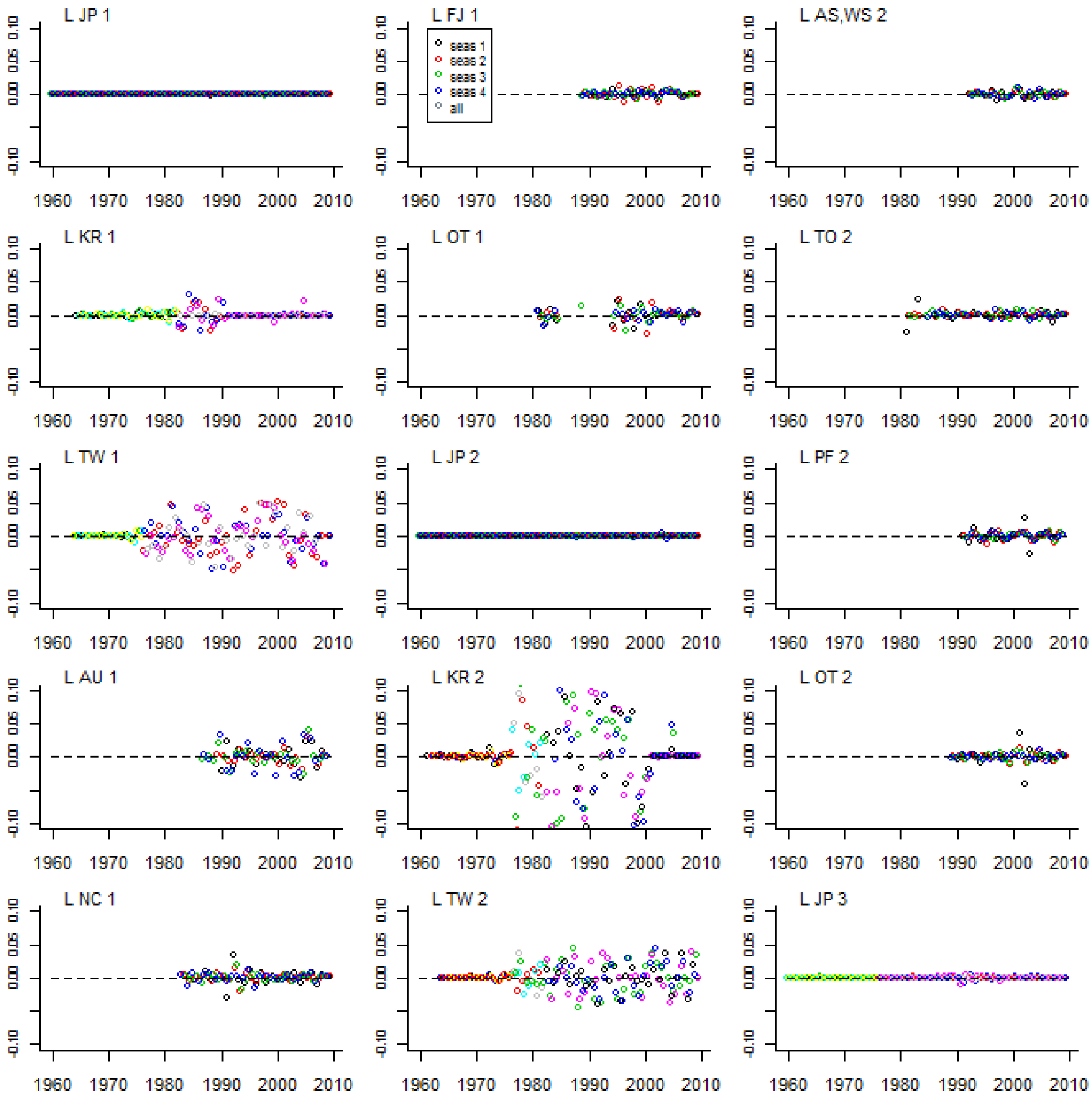

Figure 19a: Residuals of ln (total catch) for each fishery.

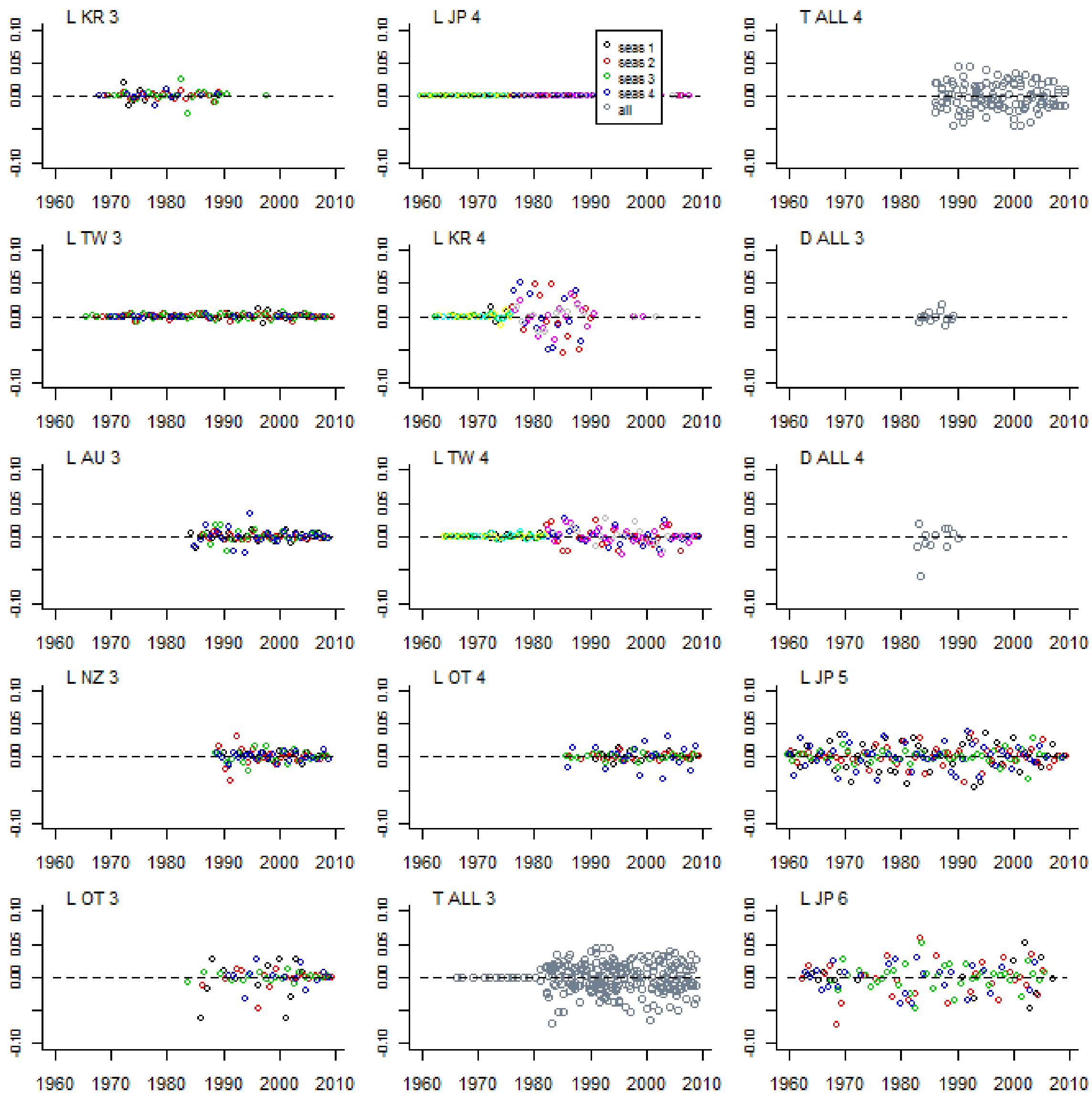

Figure 19b: Residuals of ln (total catch) for each fishery.

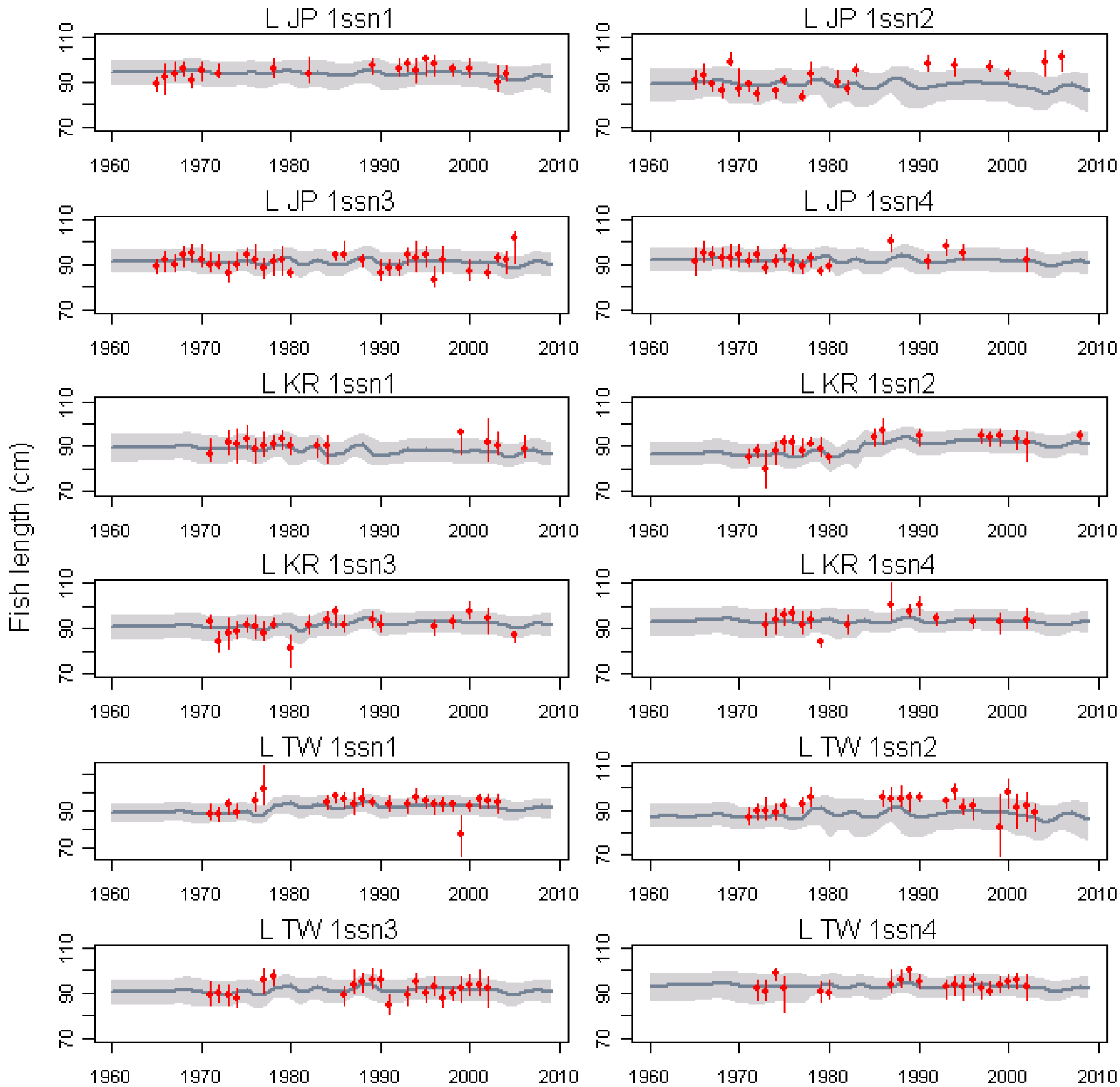

Figure 20 a: A comparison of the observed (red points) and predicted (grey line) median fish length (FL, cm) of albacore tuna by fishery for the main fisheries with length data. 'ssn' represents season. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated by year and only length samples with a minimum of 30 fish per year are plotted**.**

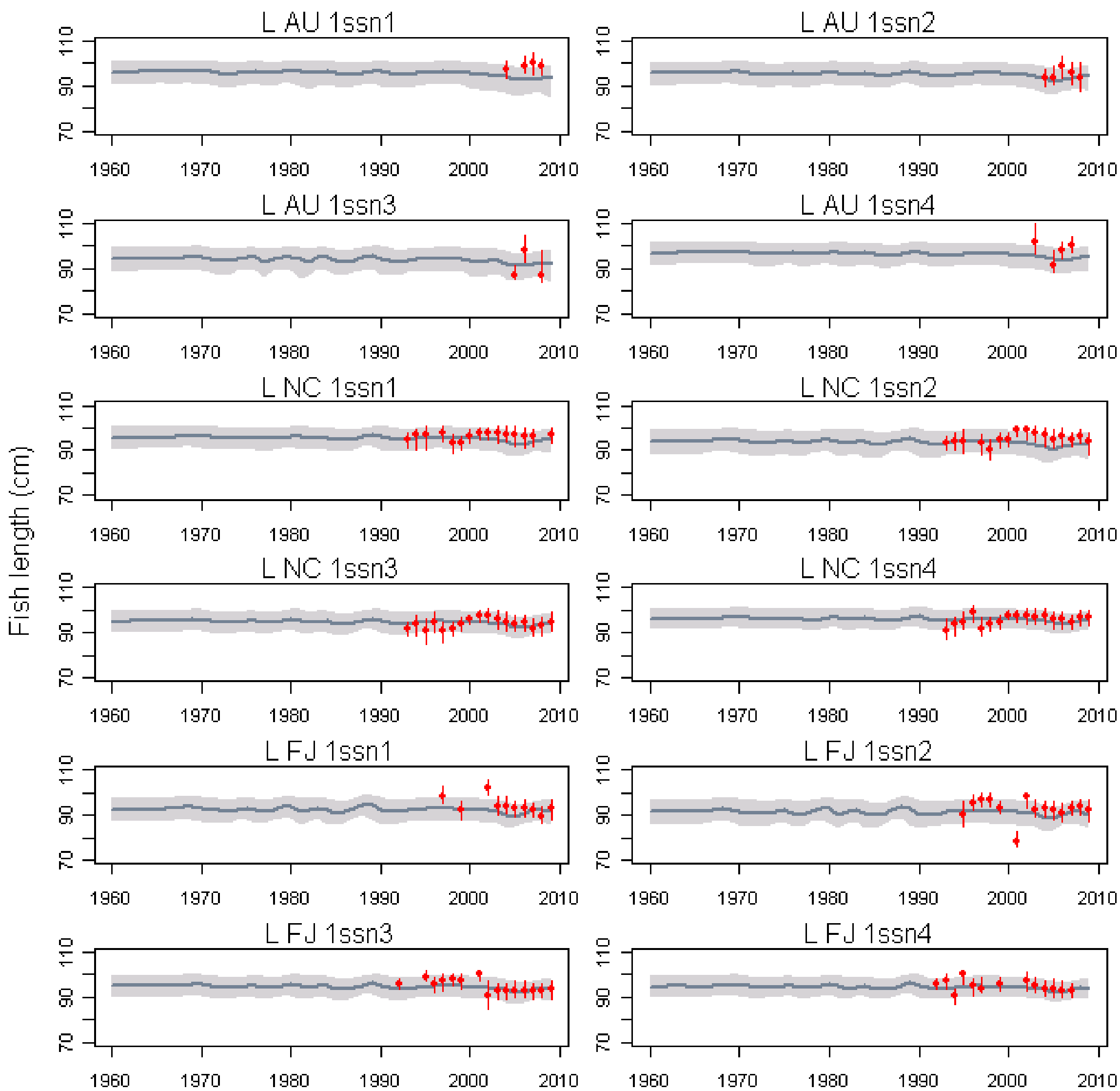

Figure 20b: A comparison of the observed (red points) and predicted (grey line) median fish length (FL, cm) of albacore tuna by fishery for the main fisheries with length data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated by year and only length samples with a minimum of 30 fish per year are plotted**.**

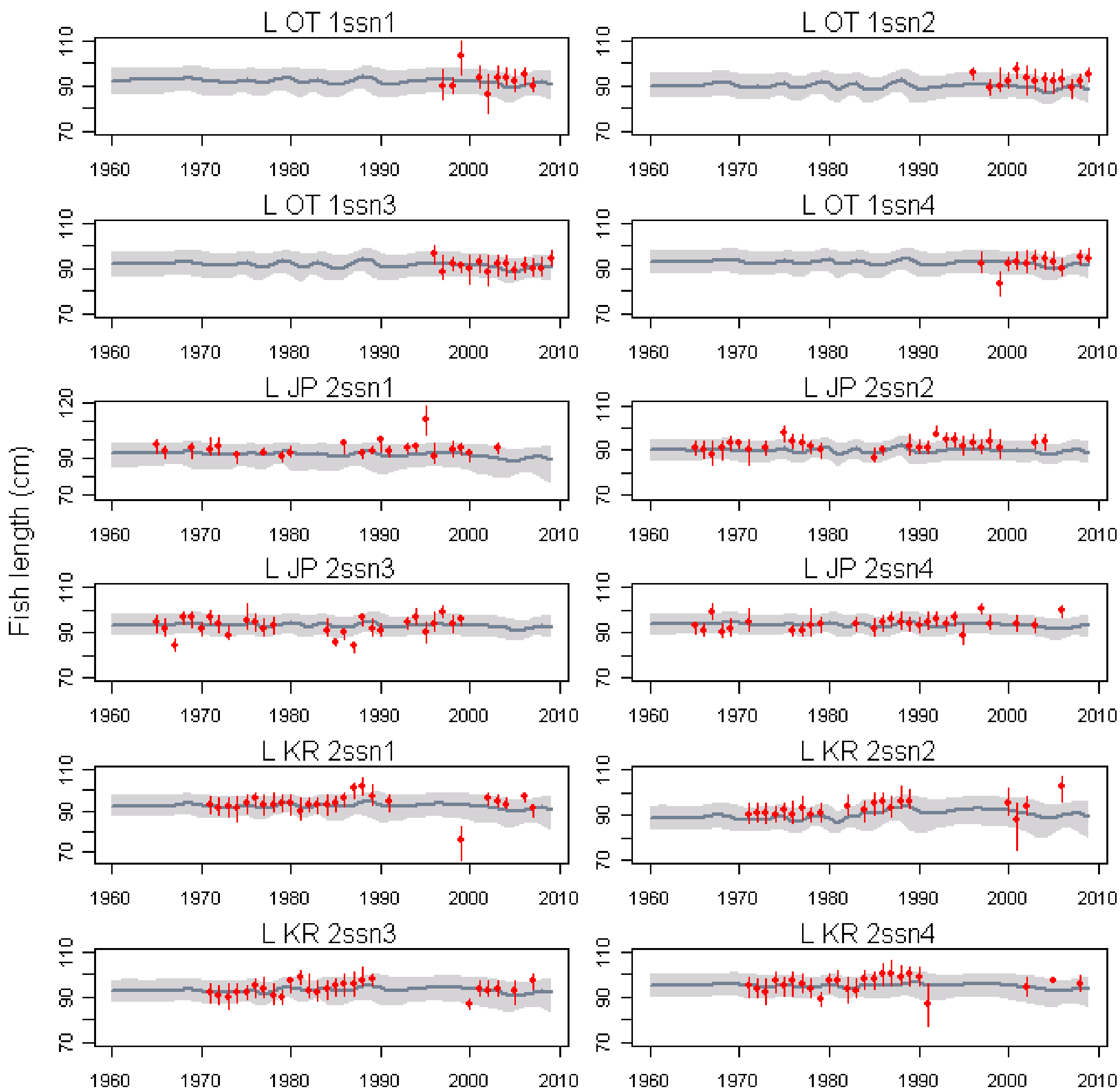

Figure 20c: A comparison of the observed (red points) and predicted (grey line) median fish length (FL, cm) of albacore tuna by fishery for the main fisheries with length data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated by year and only length samples with a minimum of 30 fish per year are plotted**.**

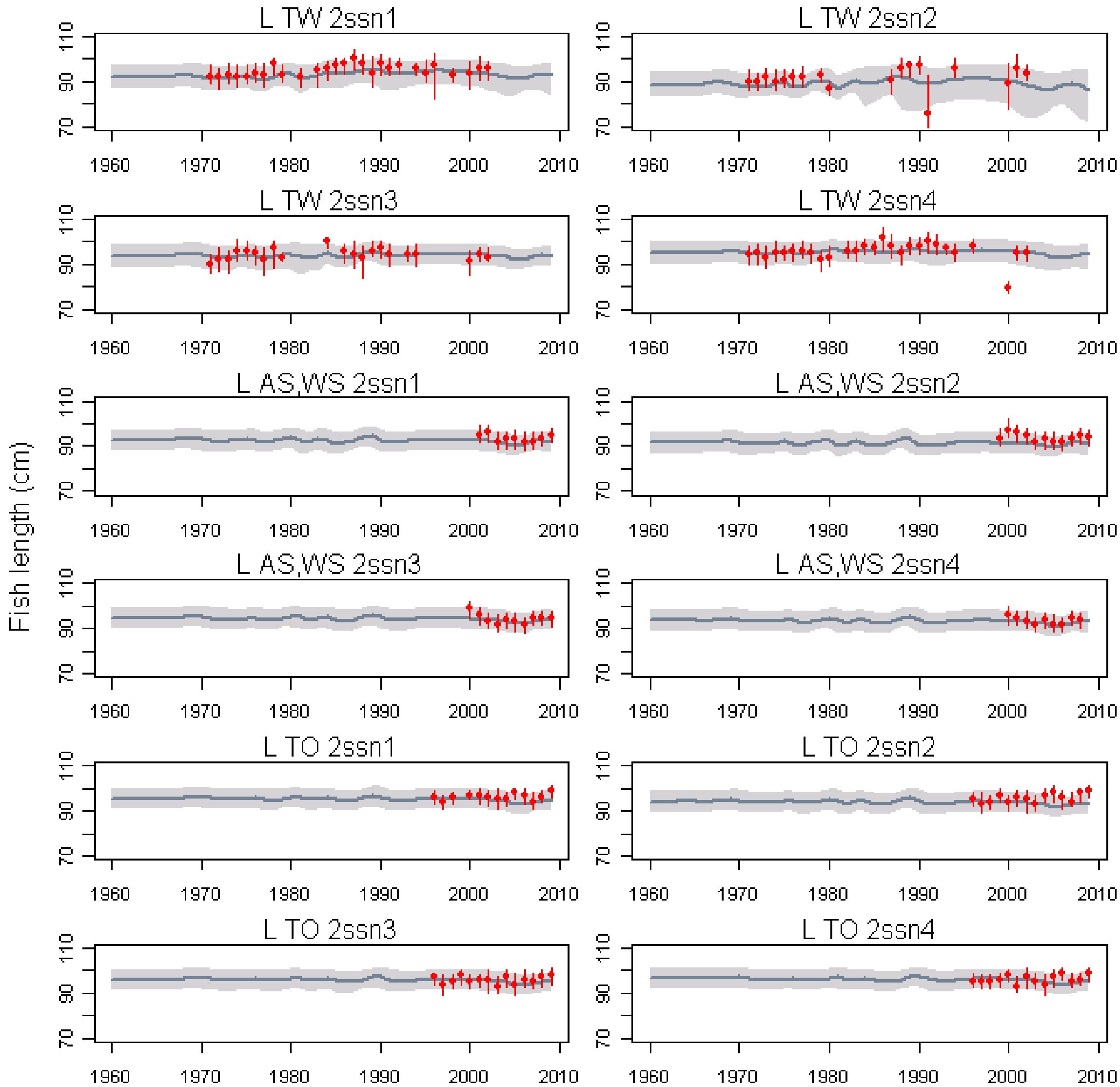

Figure 20 d: A comparison of the observed (red points) and predicted (grey line) median fish length (FL, cm) of albacore tuna by fishery for the main fisheries with length data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated by year and only length samples with a minimum of 30 fish per year are plotted**.**

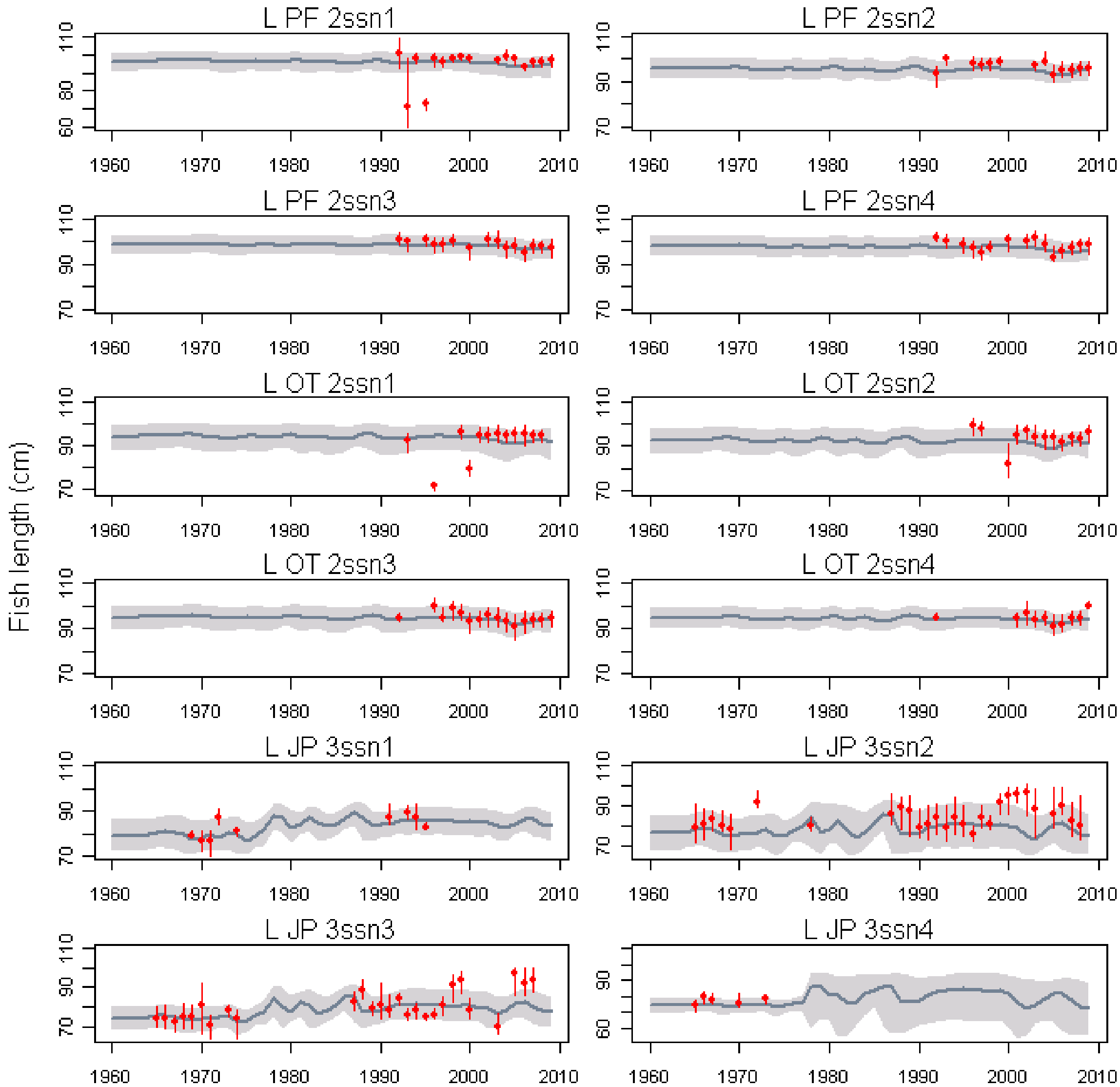

Figure 20 e: A comparison of the observed (red points) and predicted (grey line) median fish length (FL, cm) of albacore tuna by fishery for the main fisheries with length data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated by year and only length samples with a minimum of 30 fish per year are plotted.

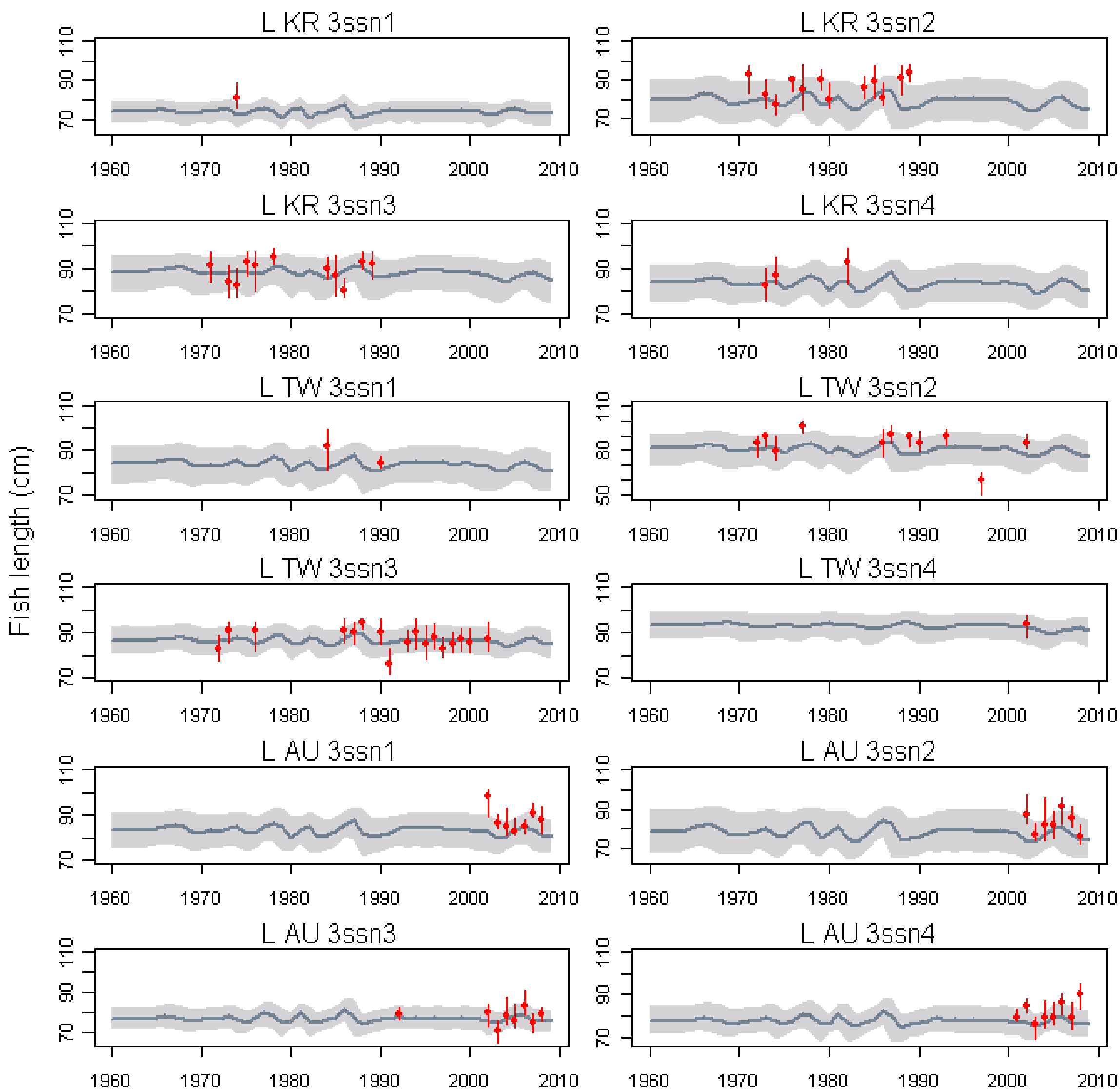

Figure 20f: A comparison of the observed (red points) and predicted (grey line) median fish length (FL, cm) of albacore tuna by fishery for the main fisheries with length data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated by year and only length samples with a minimum of 30 fish per year are plotted**.**

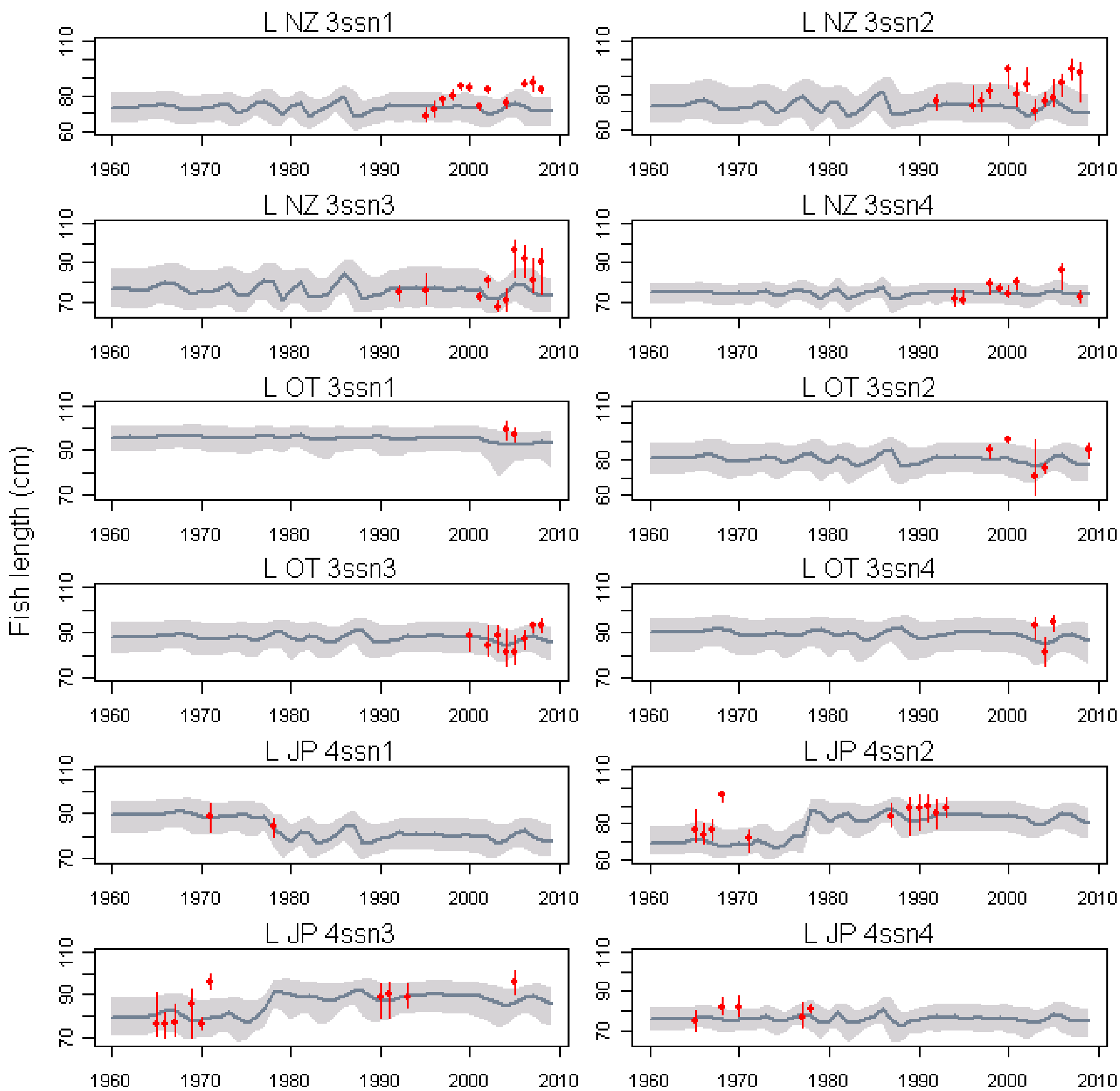

Figure 20 g: A comparison of the observed (red points) and predicted (grey line) median fish length (FL, cm) of albacore tuna by fishery for the main fisheries with length data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated by year and only length samples with a minimum of 30 fish per year are plotted**.**

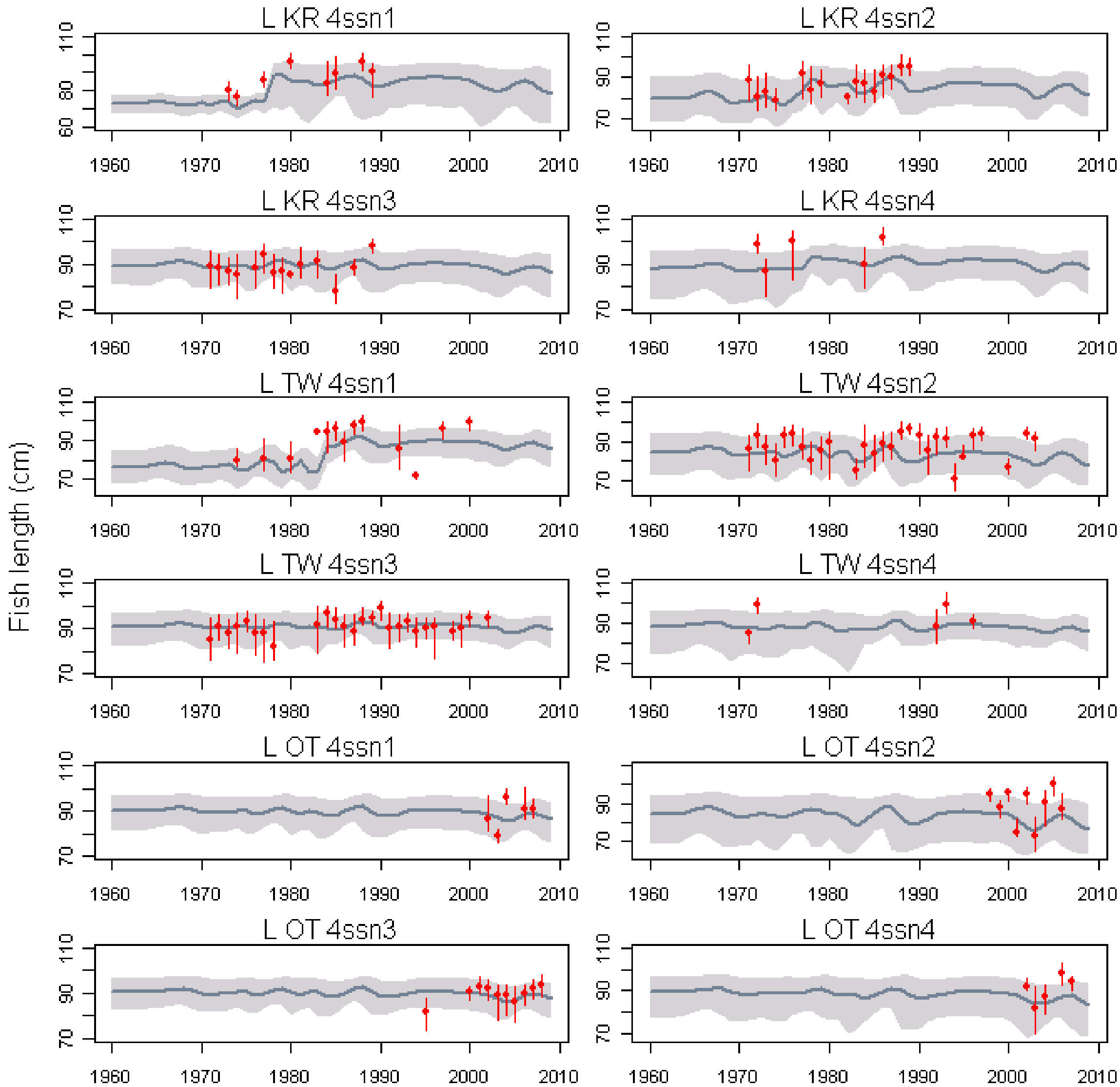

Figure 20h: A comparison of the observed (red points) and predicted (grey line) median fish length (FL, cm) of albacore tuna by fishery for the main fisheries with length data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated by year and only length samples with a minimum of 30 fish per year are plotted**.**

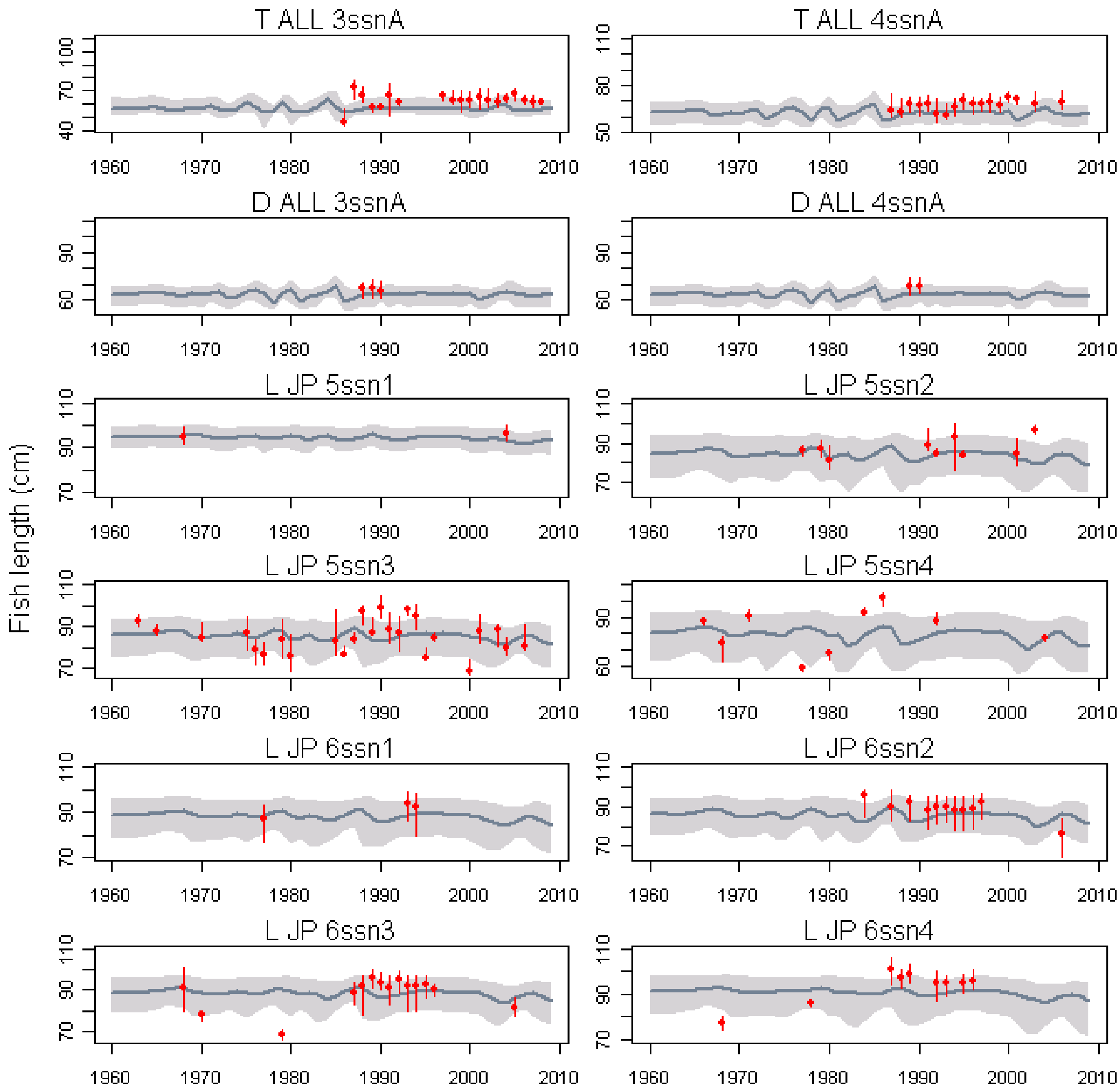

Figure 20i: A comparison of the observed (red points) and predicted (grey line) median fish length (FL, cm) of albacore tuna by fishery for the main fisheries with length data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated by year and only length samples with a minimum of 30 fish per year are plotted**.**

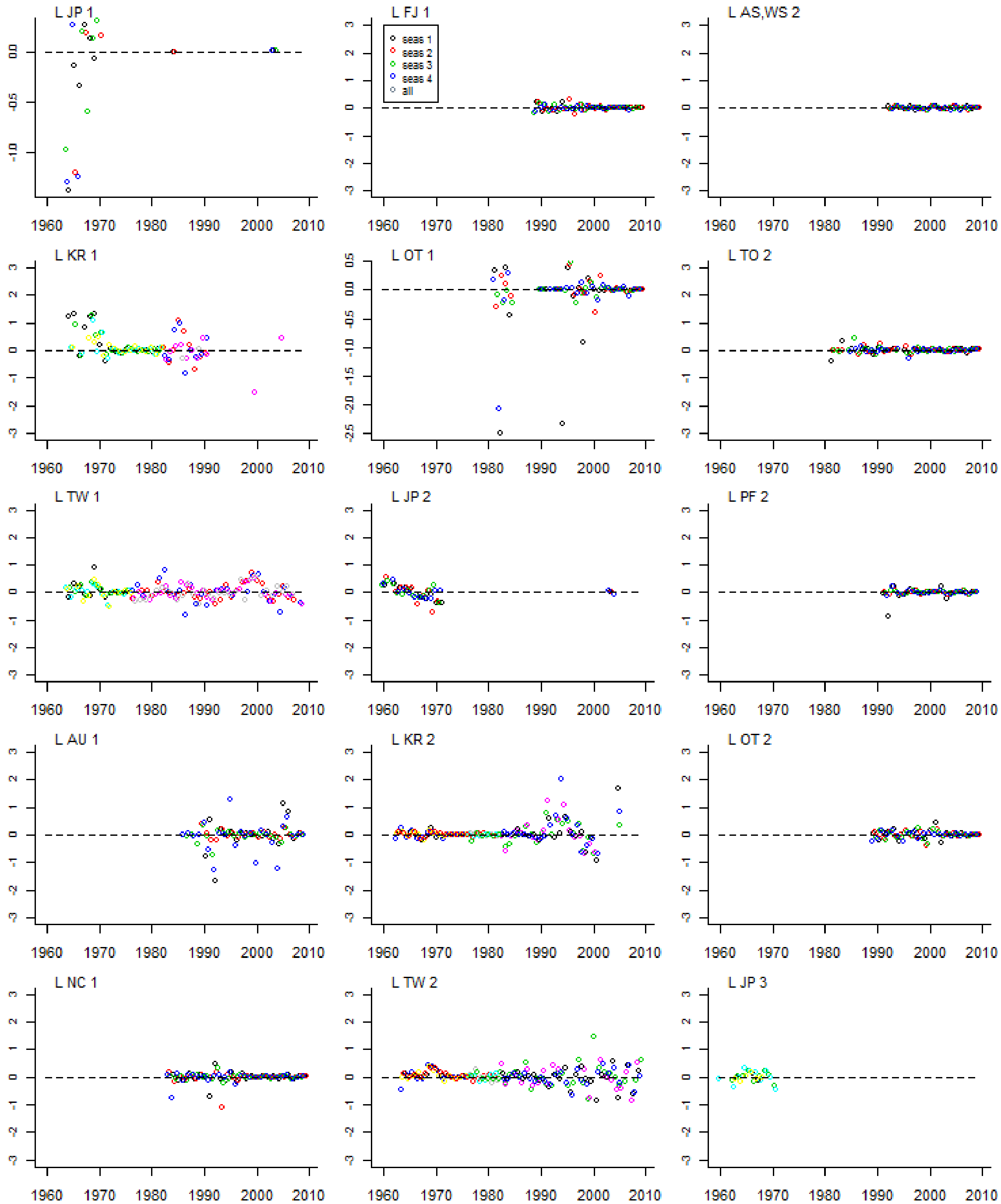

Figure 21a: Quarterly effort deviates by fishery.

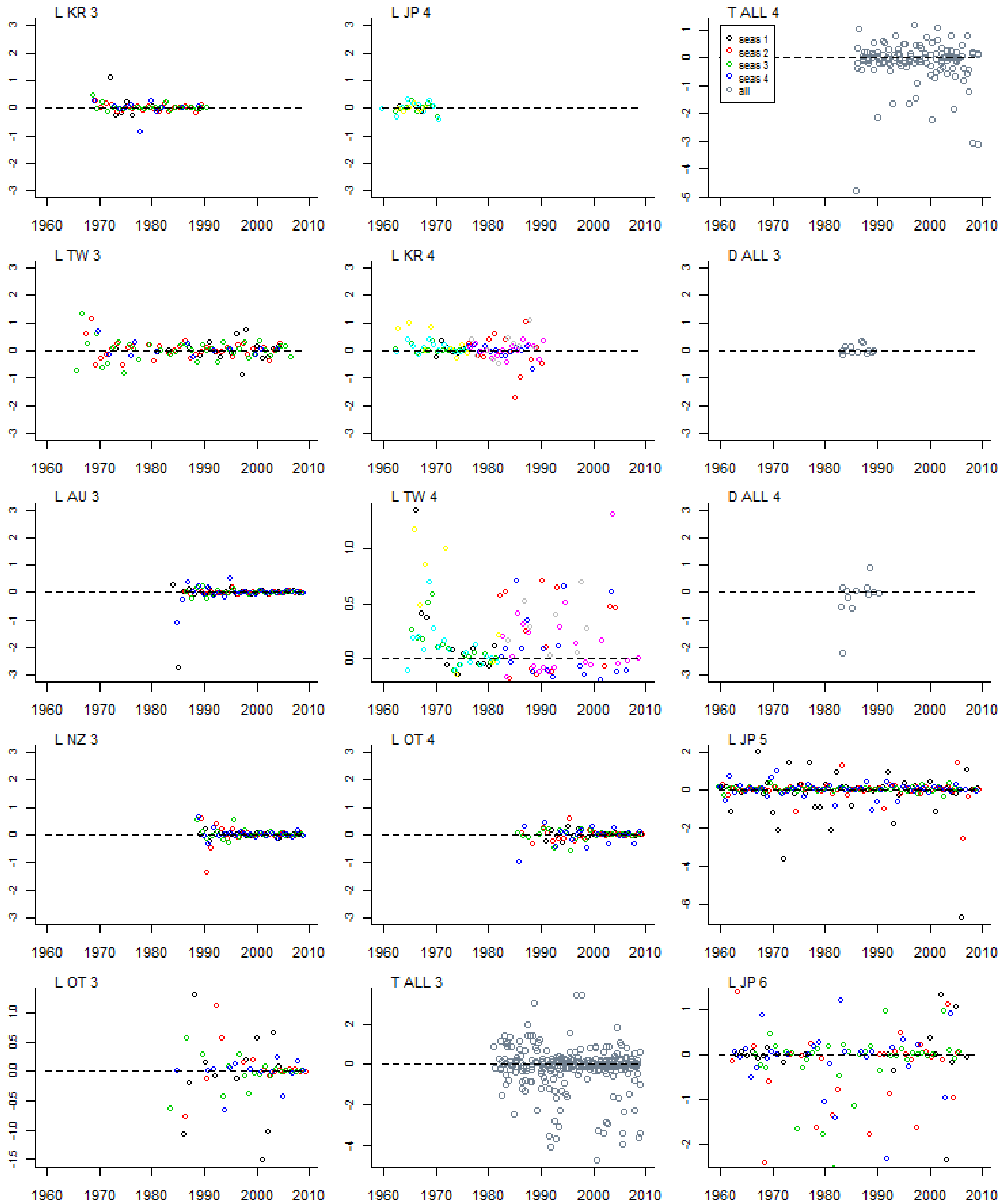

Figure 21b: Quarterly effort deviates by fishery.

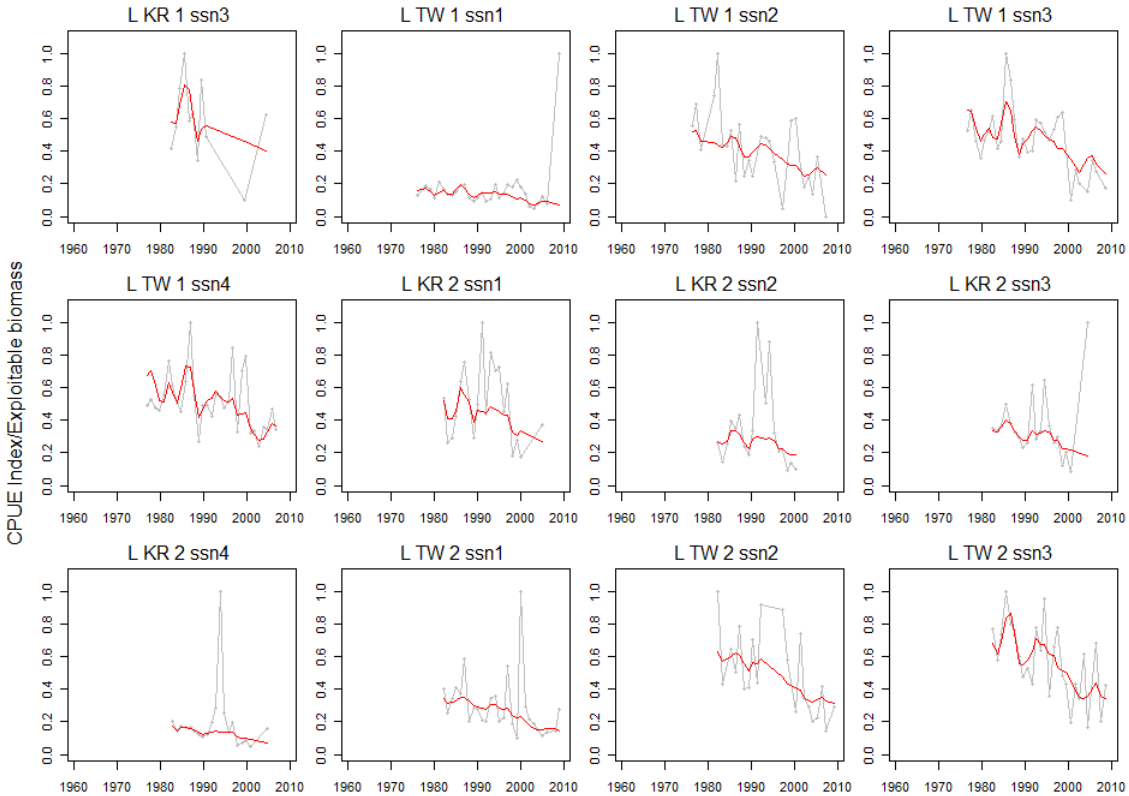

Figure 22a: A comparison of the observed catch rate (number of fish) (grey points and line) and the predicted exploitable biomass from the quarterly observations of catch and effort from each of the standardised fisheries (red line).

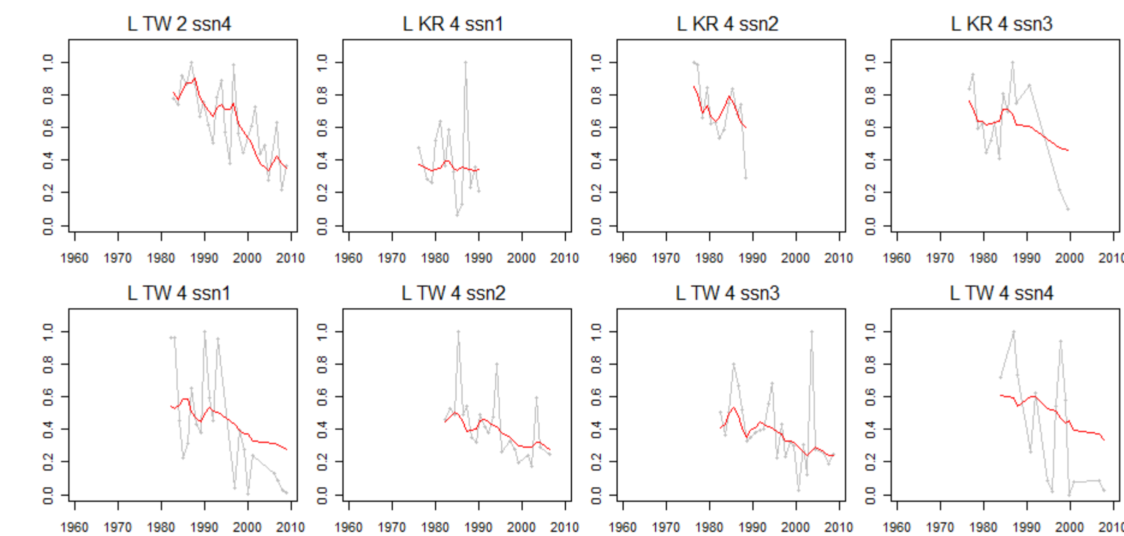

Figure 22b: A comparison of the observed catch rate (number of fish) (grey points and line) and the predicted exploitable biomass from the quarterly observations of catch and effort from each of the standardised fisheries (red line).

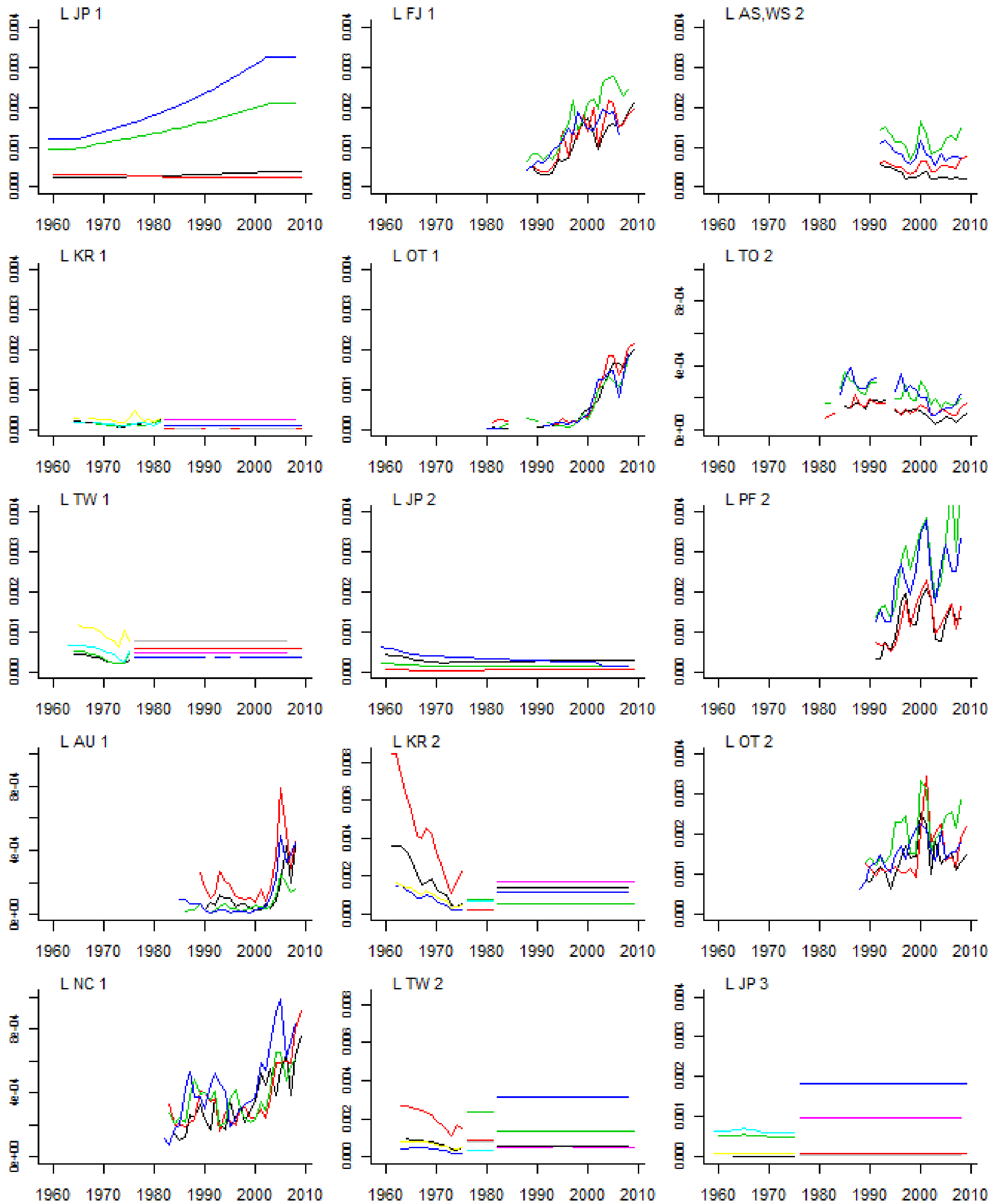

Figure 23a: Annualised trends in catchability by fishery. The different coloured lines show the patterns by season.

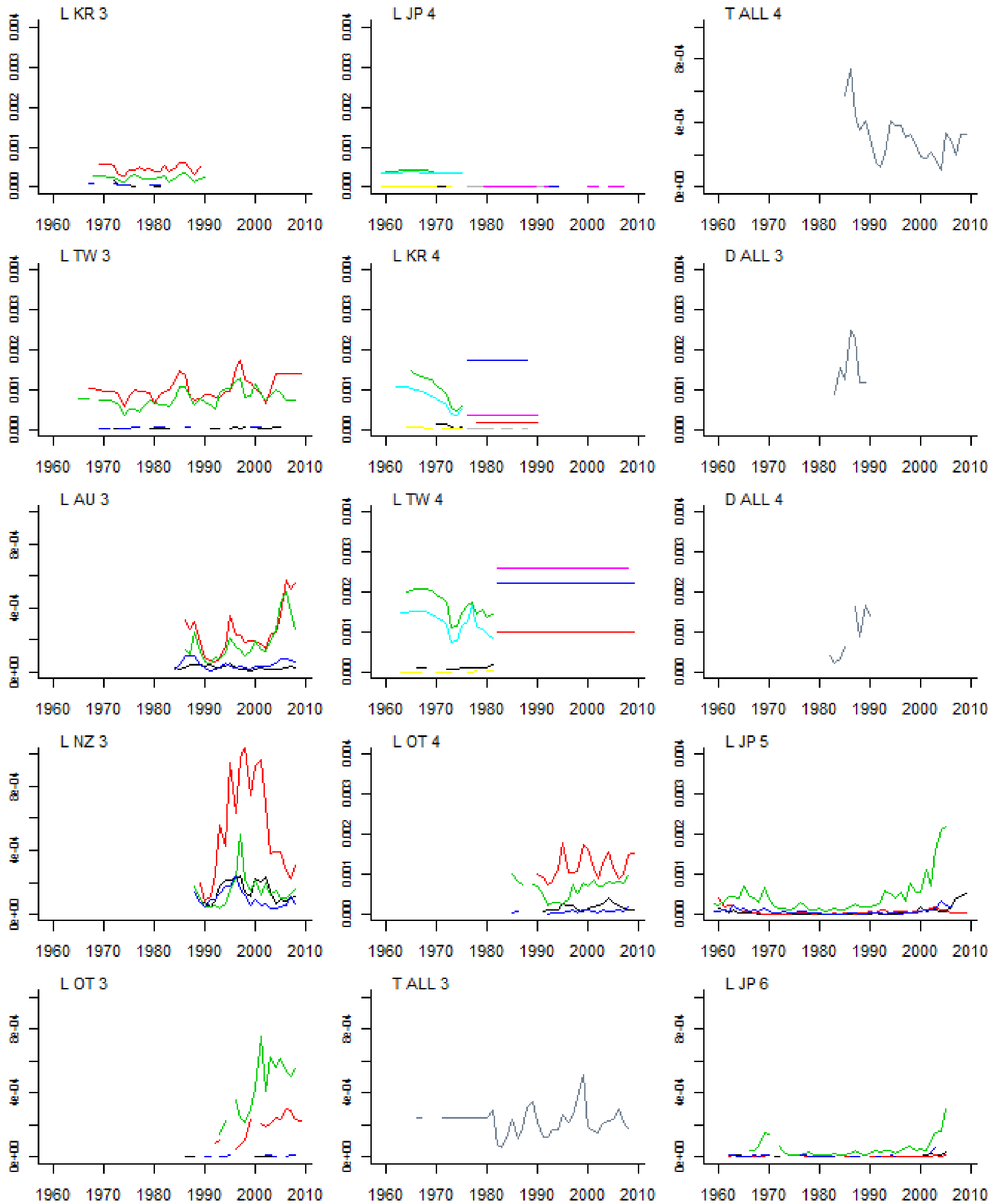

Figure 23b: Annualised trends in catchability by fishery. The different coloured lines show the patterns by season.

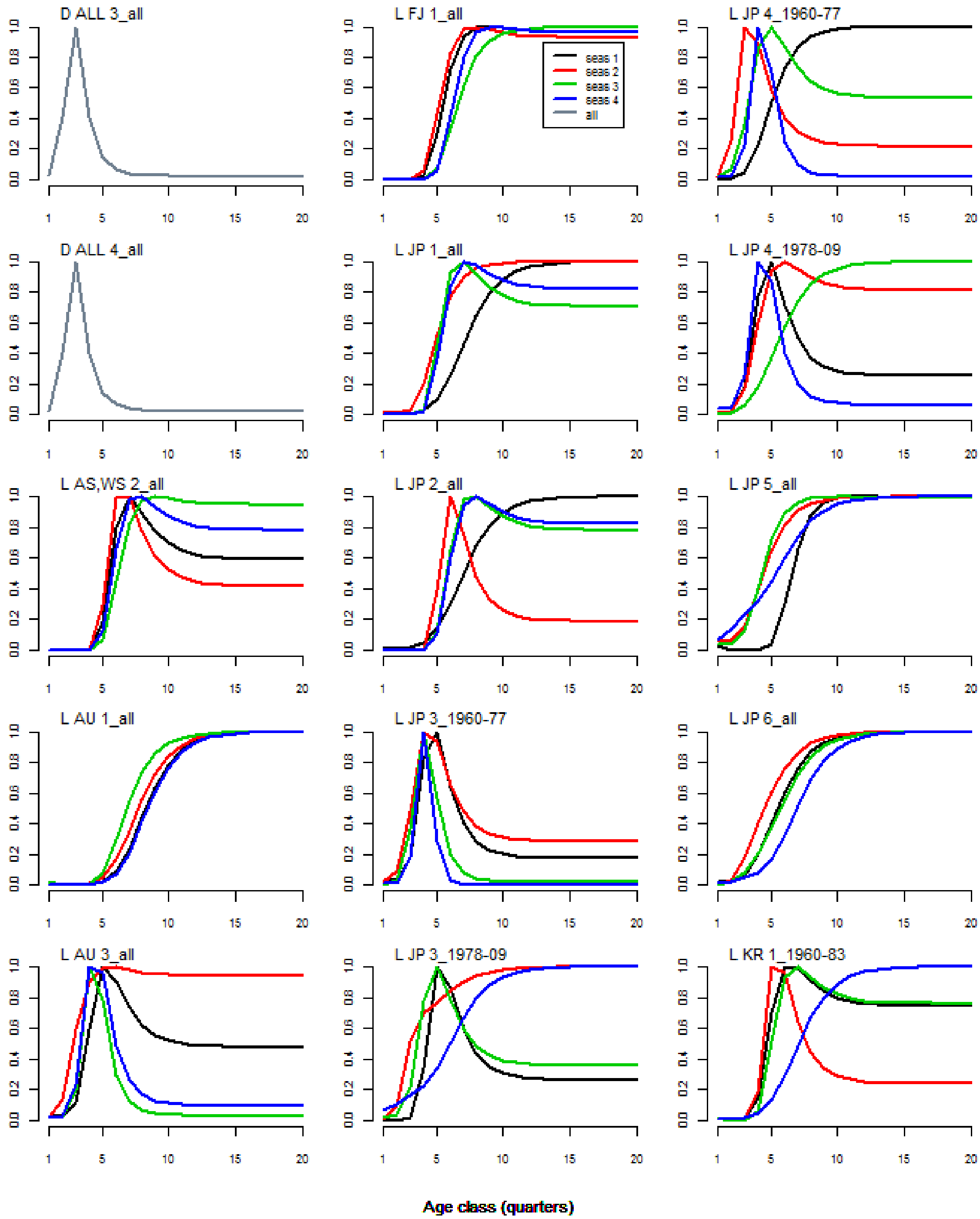

Figure 24a: Selectivity at age (years) by fishery. The different coloured lines show the patterns by season.

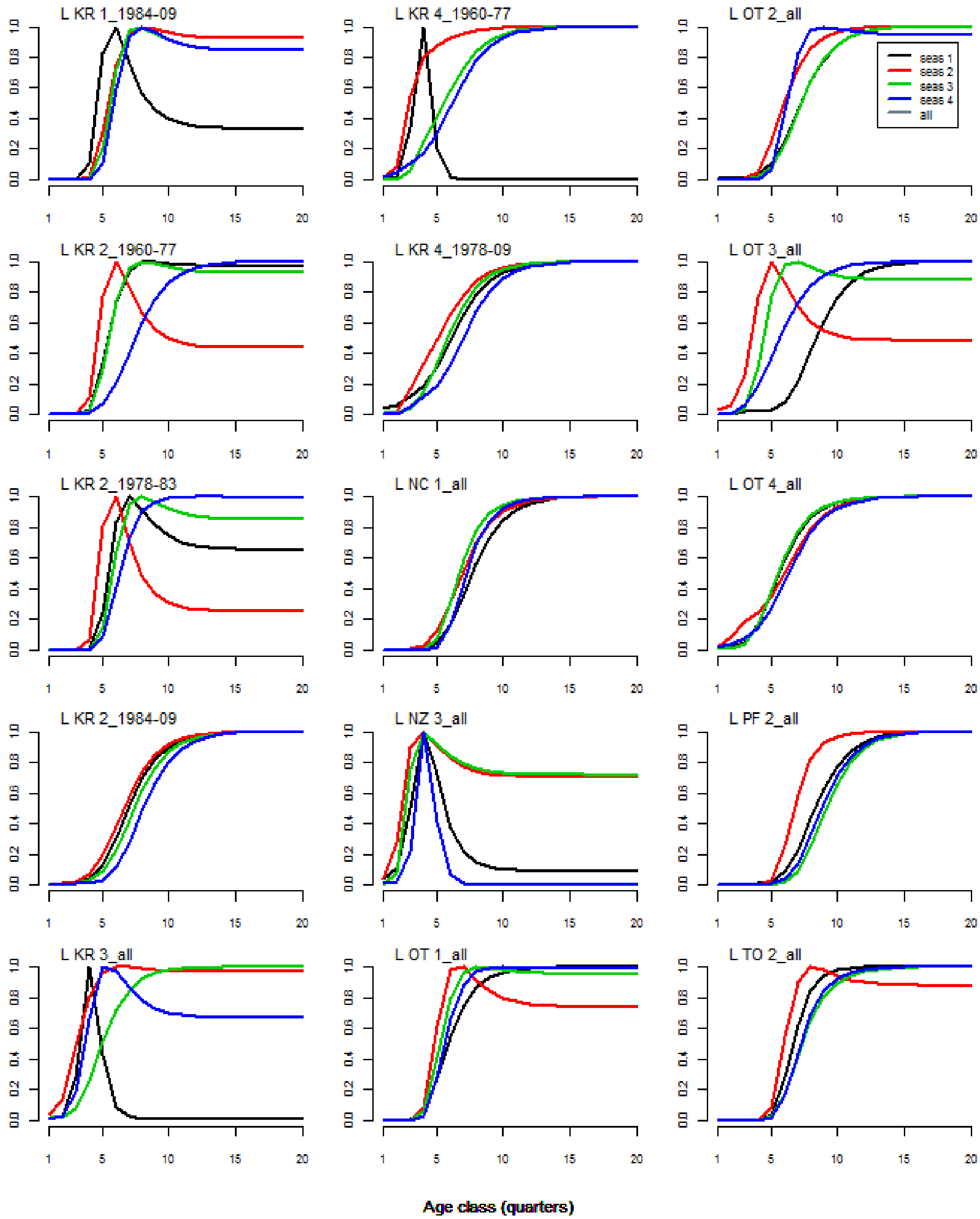

Figure 24b: Selectivity at age (years) by fishery. The different coloured lines show the patterns by season.

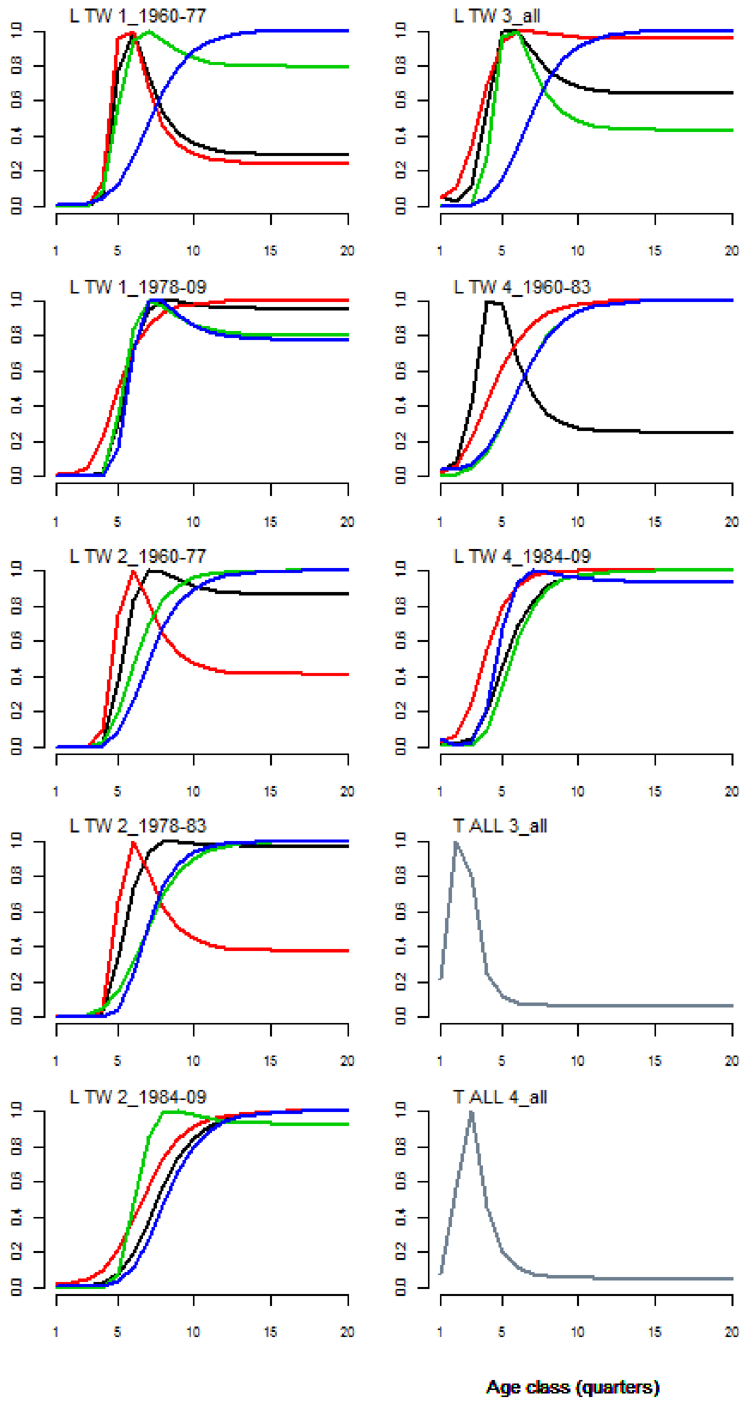

Figure 24c: Selectivity at age (years) by fishery. The different coloured lines show the patterns by season.

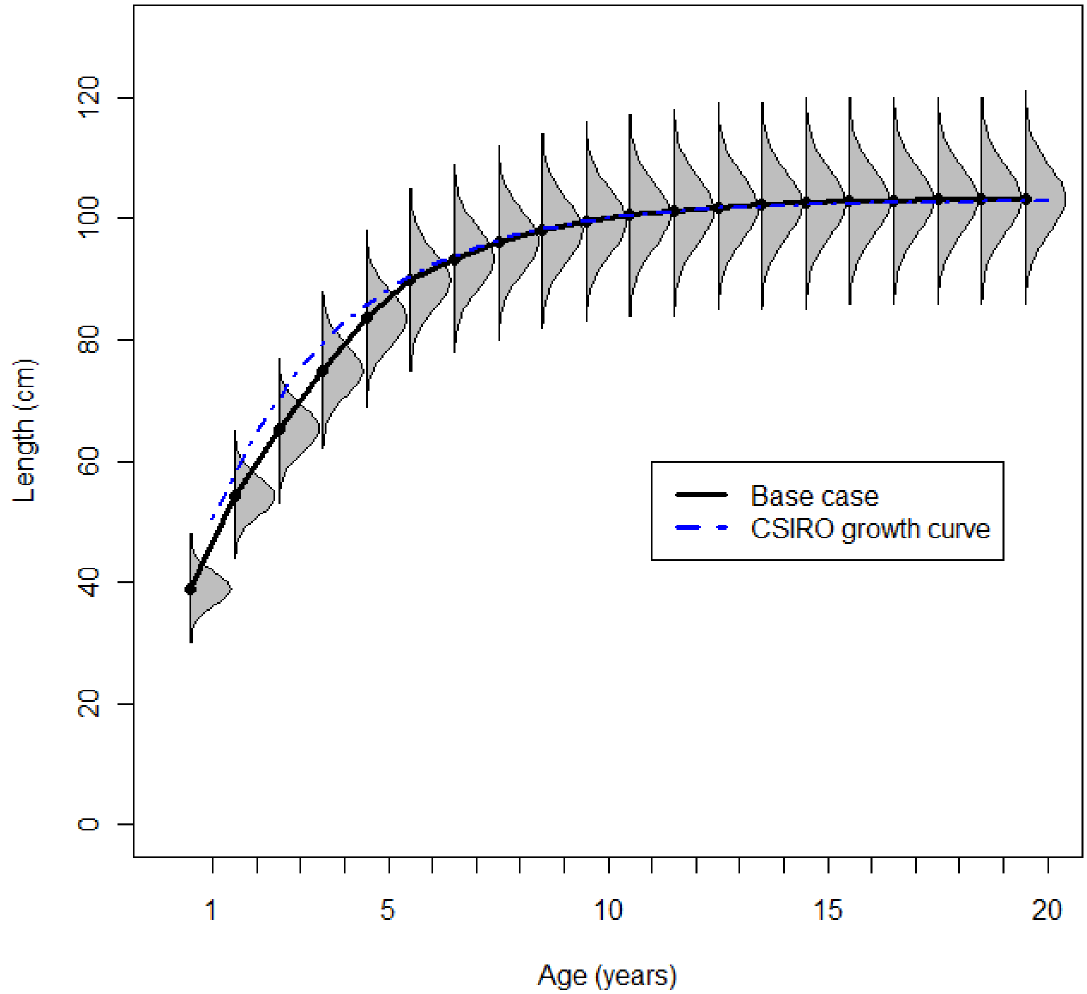

Figure 25: Estimated length (fork length) at age (years) (solid line) and the 95% confidence interval. The dashed line represents the curve calculated using the initial von Bertalanffy parameter values included in the model.

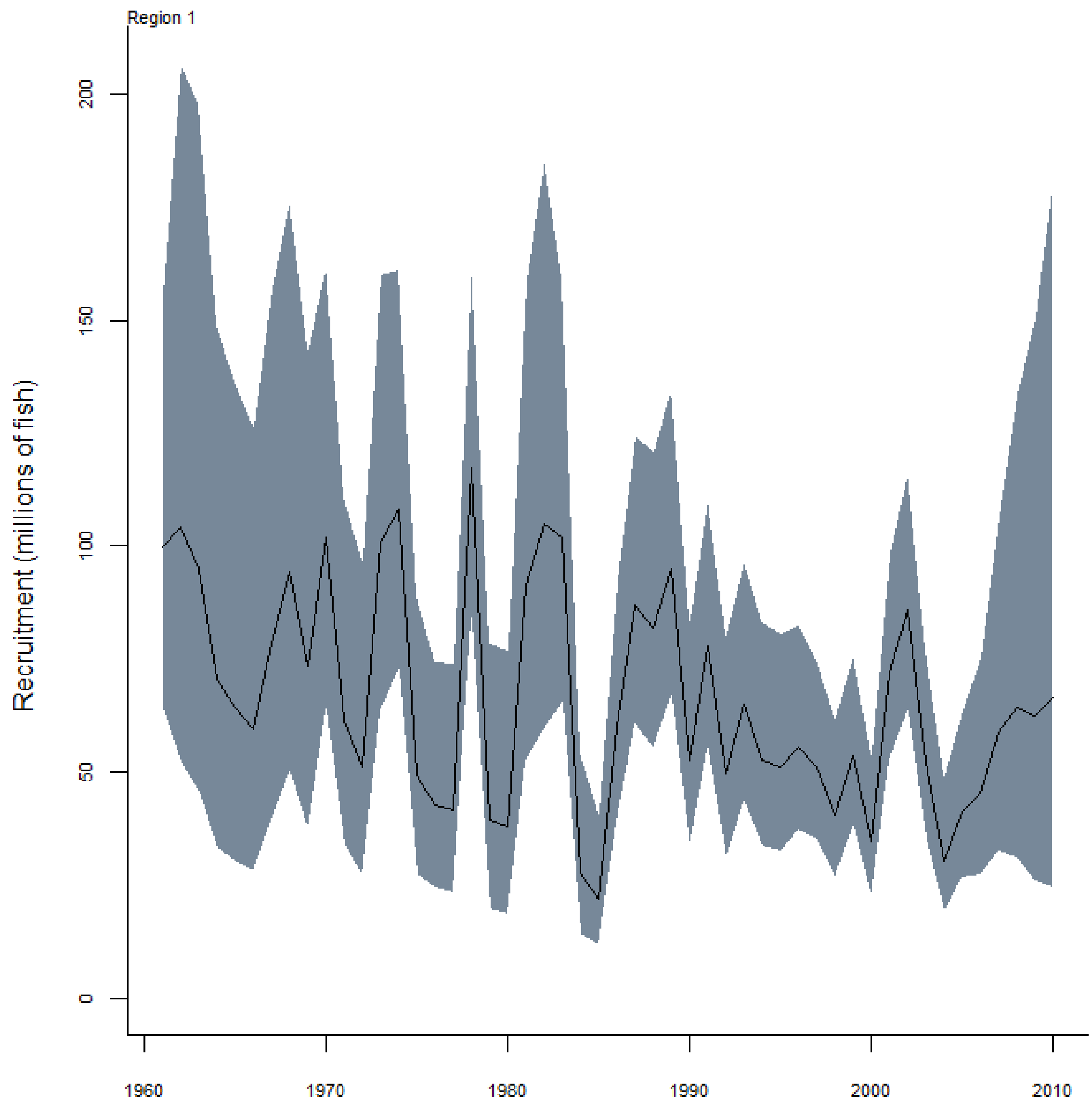

Figure 26: Annual recruitment (number of fish) estimates. The grey area represents parameter uncertainty estimated from the Hessian matrix.

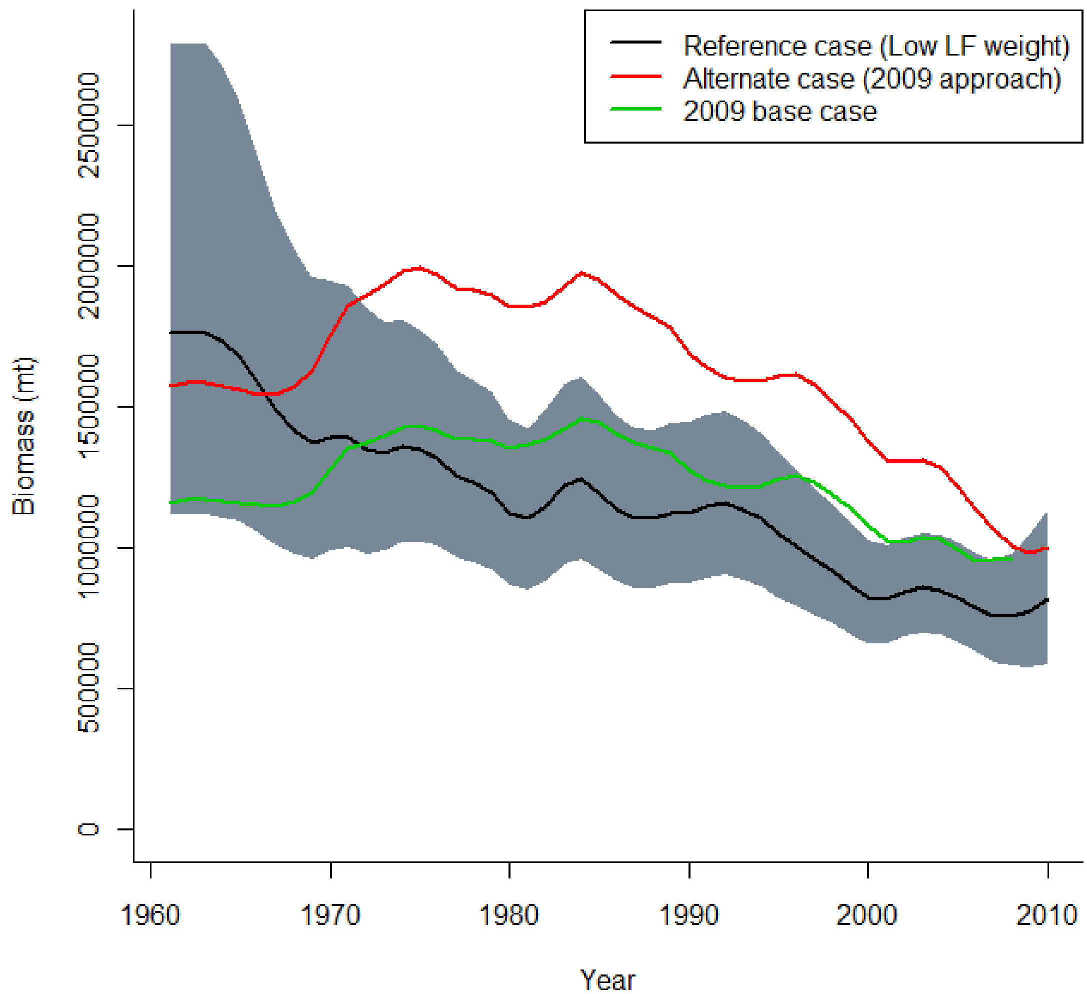

Figure 27: Annual estimates of total biomass (thousands of metric tonnes). Several scenarios are shown to illustrate the change between this year's reference case, the alternate case that used the same approach as in 2009, and the biomass trend estimated in the 2009 base case. The comparisons illustrate some effects of conflict between the CPUE and the length frequency data. The grey area represents parameter uncertainty estimated from the Hessian matrix.

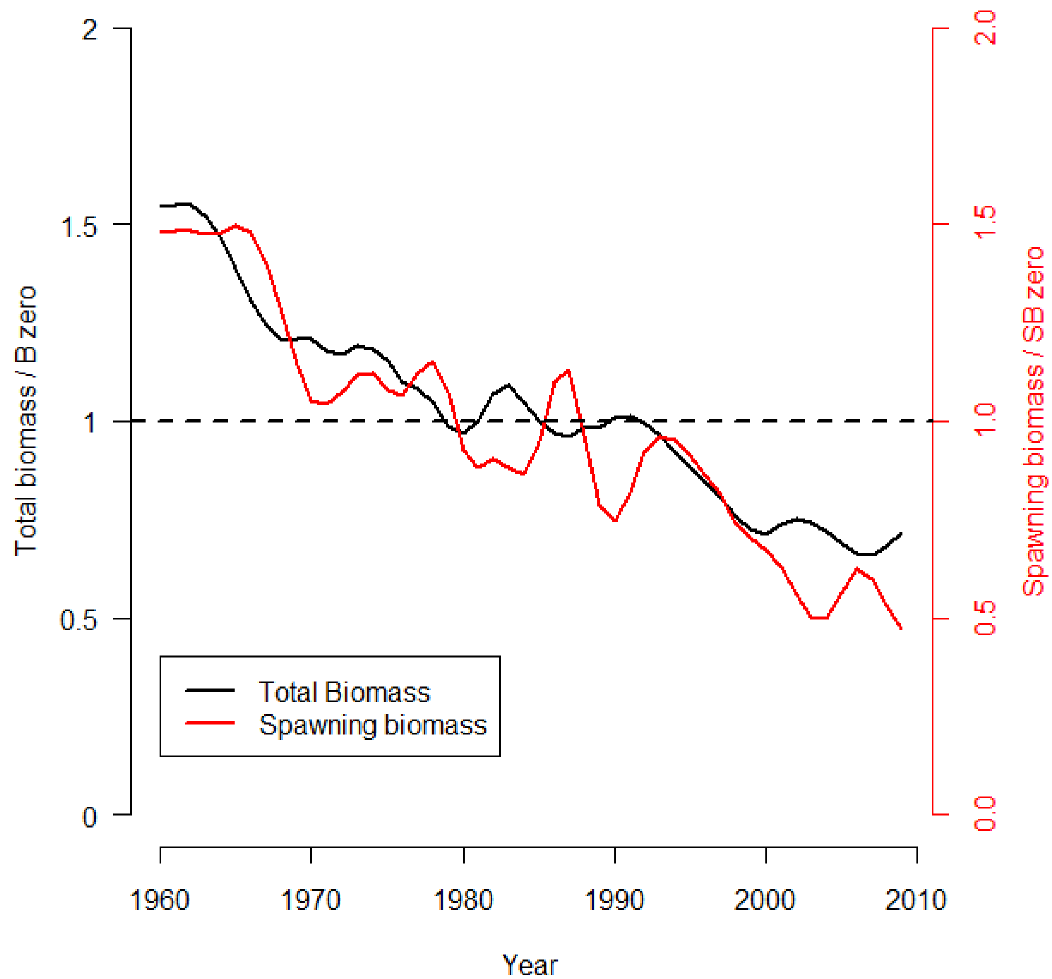

Figure 28: Time series of the ratios B / B_0 and SB / SB_0. Initial biomasses are estimated to be well above equilibrium unfished levels (represented by B_0 and SB_0).

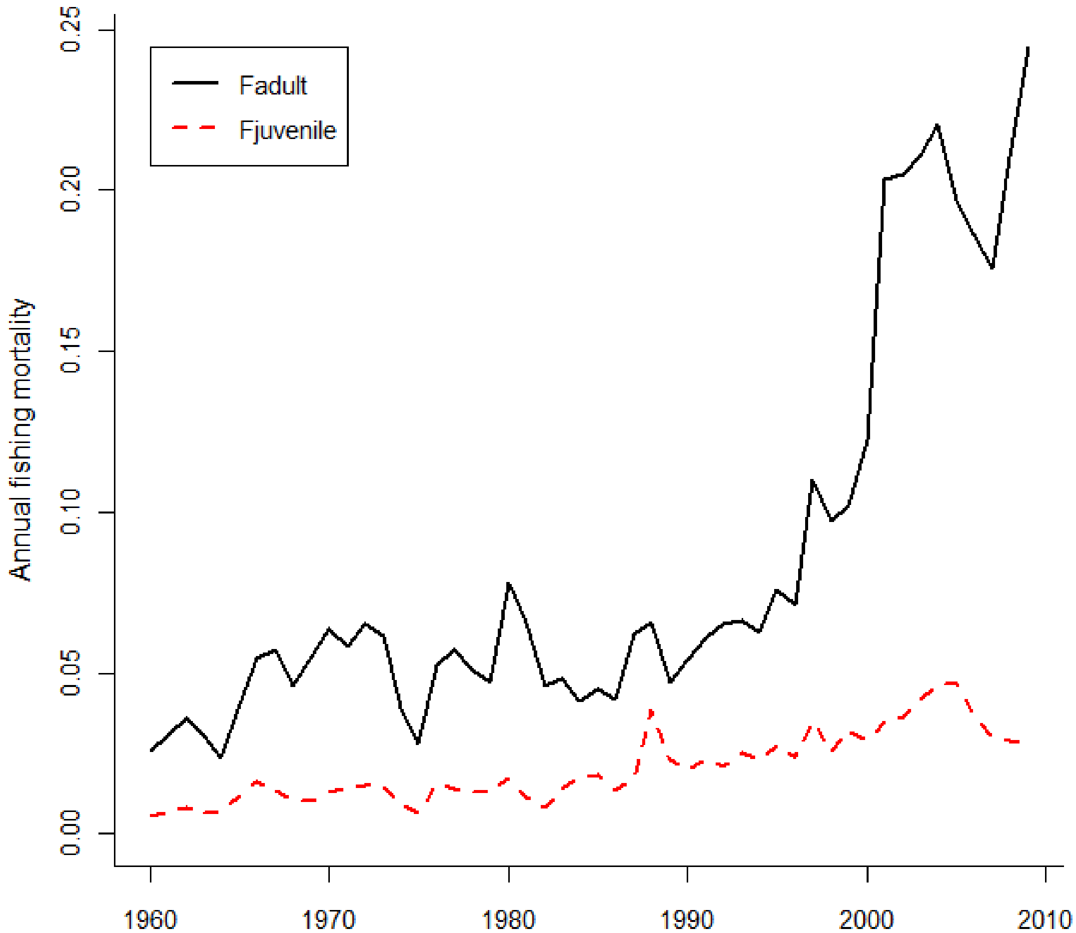

Figure 29: Annual estimates of fishing mortality for juvenile and adult South Pacific albacore.

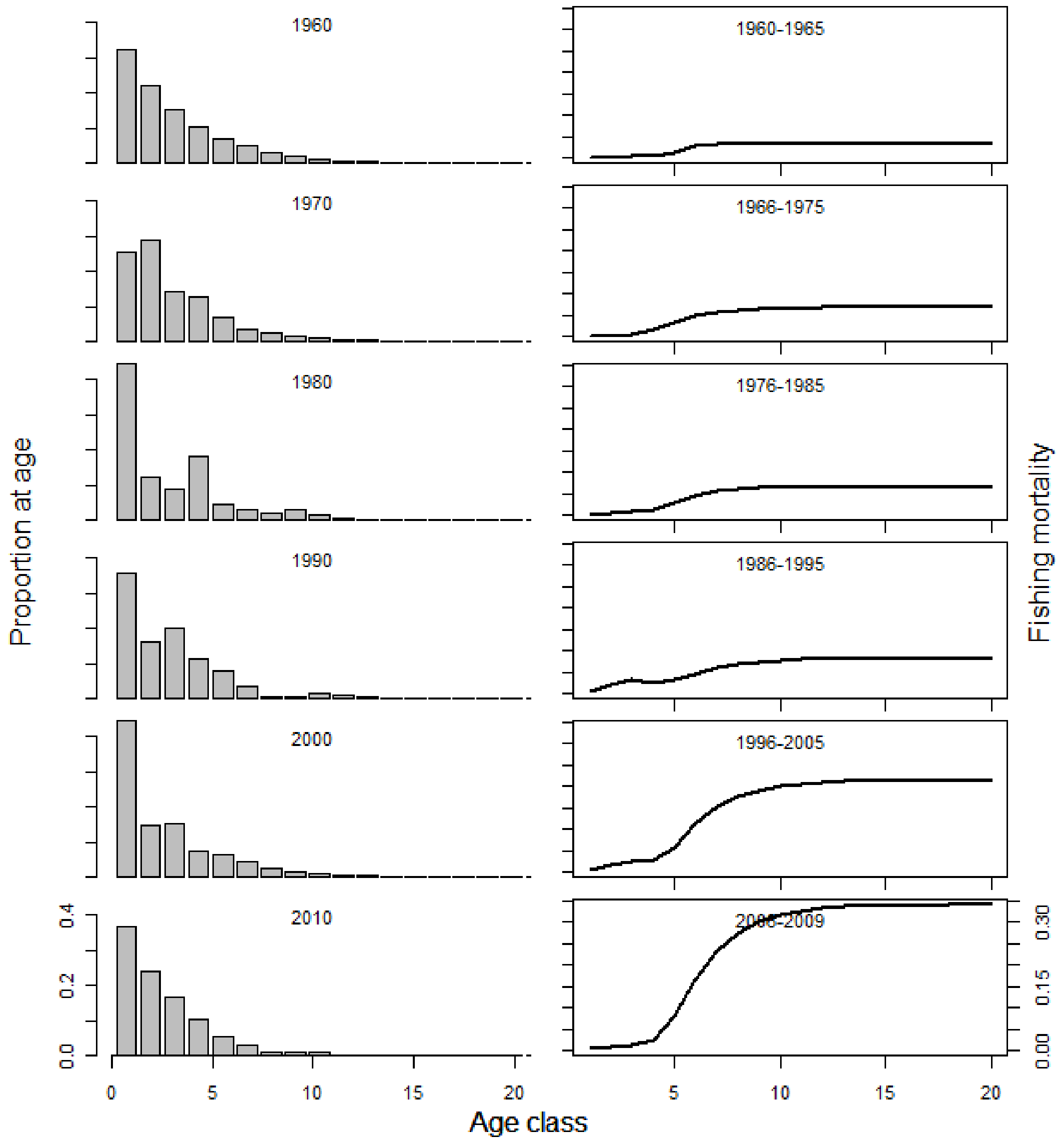

Figure 30: Estimated proportion at age (left) and mortality at age (right) by year at decadal intervals, and for 2006.

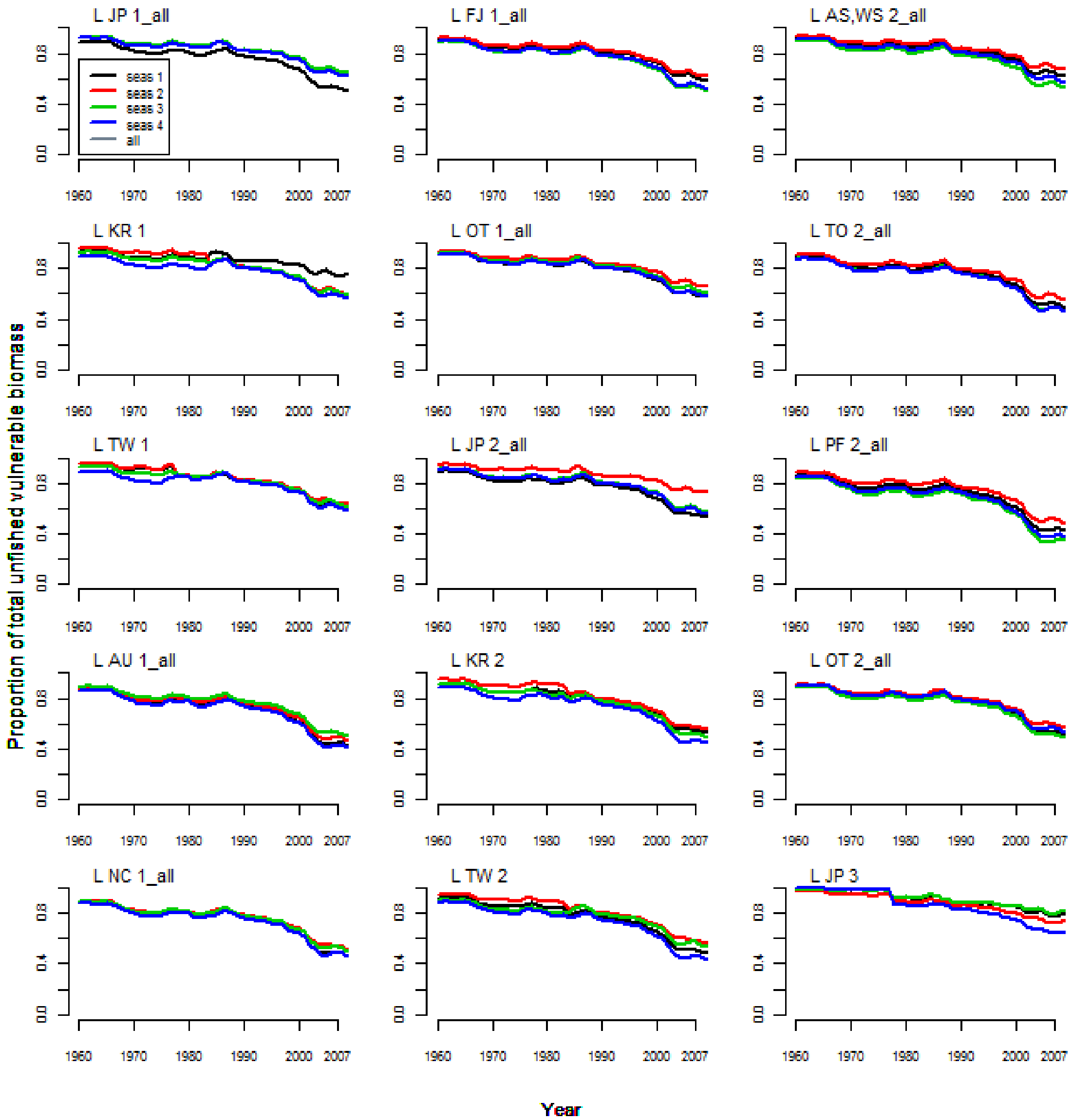

Figure 31a: The ratio between the level of exploitable biomass for individual fisheries and the level of exploitable biomass predicted in the absence of fishing.

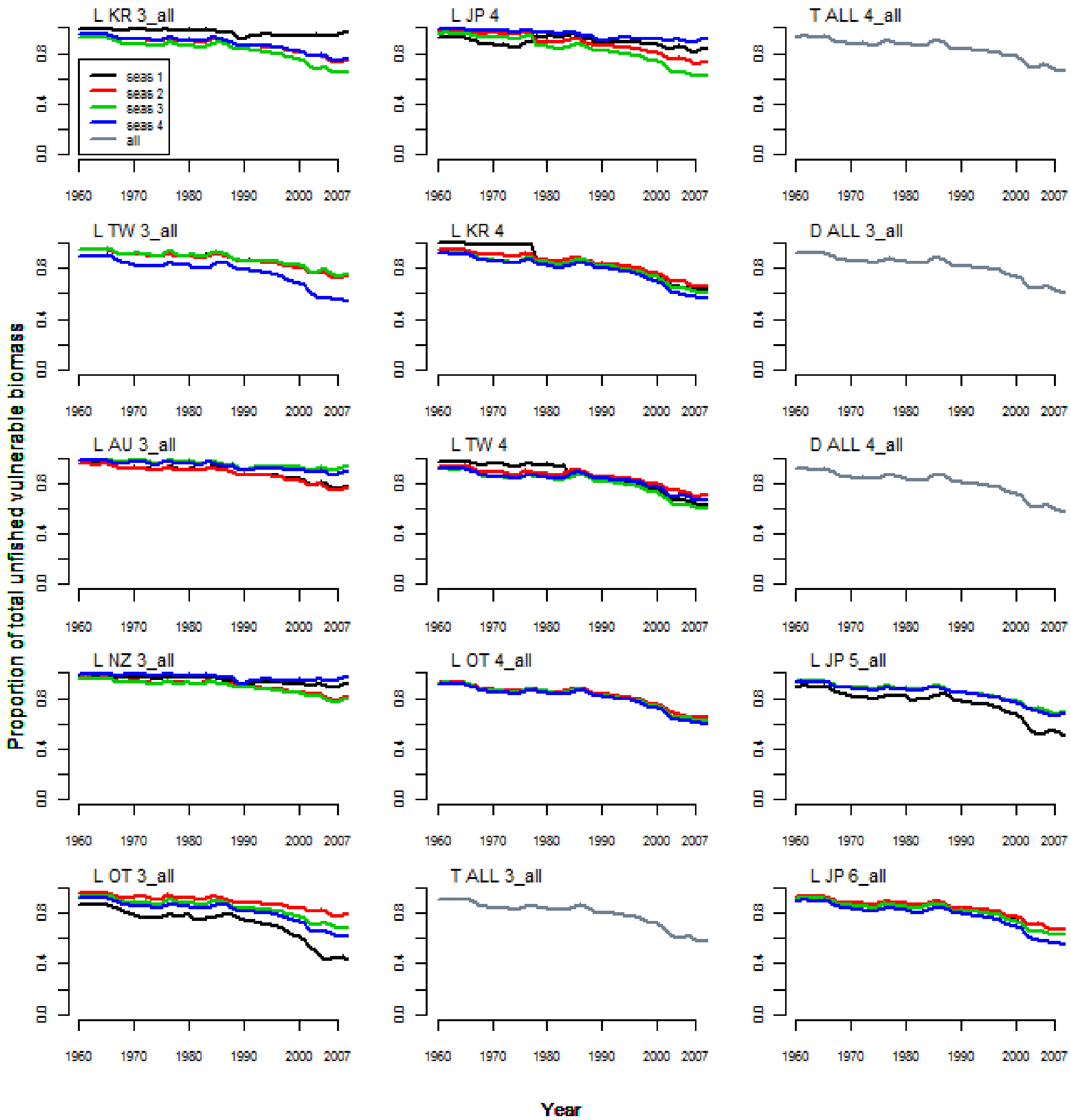

Figure 31b: The ratio between the level of exploitable biomass for individual fisheries and the level of exploitable biomass predicted in the absence of fishing.

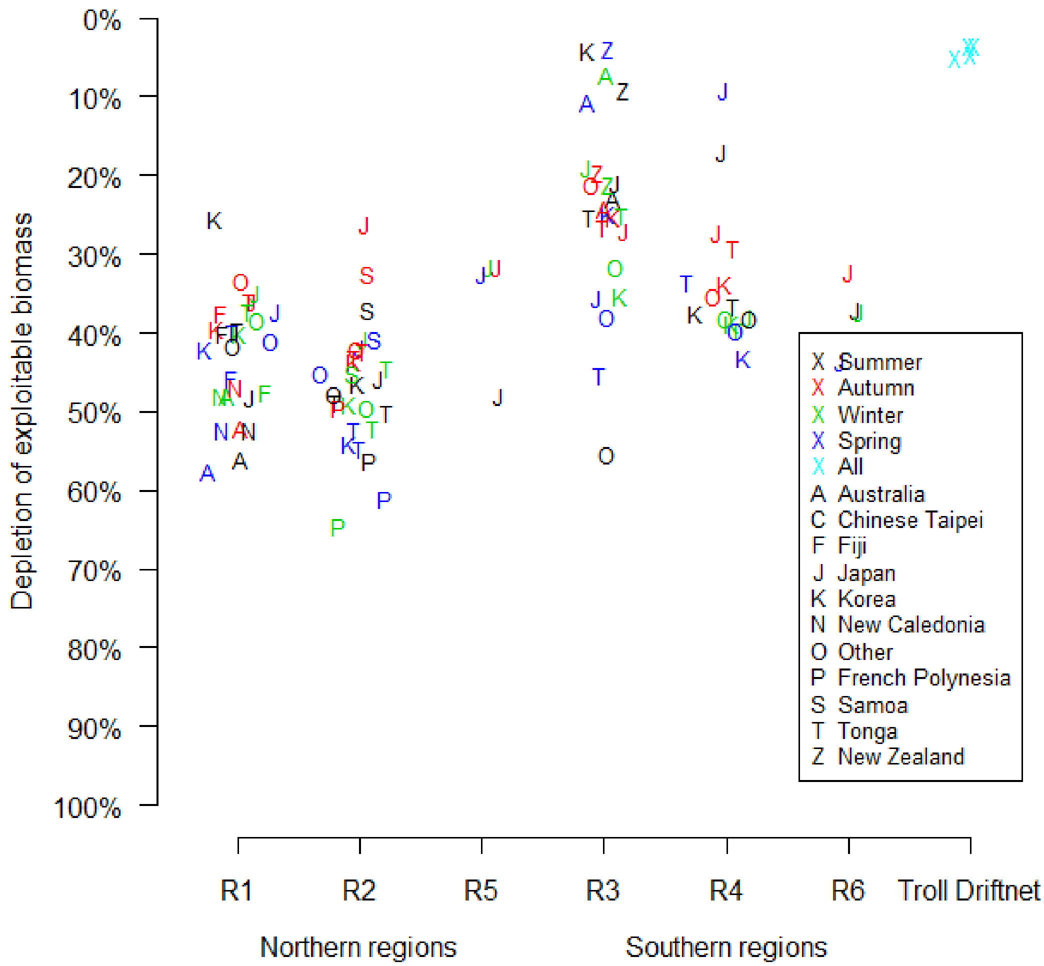

Figure 32: Average depletion (due to all fishing) of exploitable biomass by fishery for the period 2007–2009, by fishery. Fisheries are coloured by season, and labelled according to fishing nation. The four light blue crosses represent the troll and driftnet fisheries.

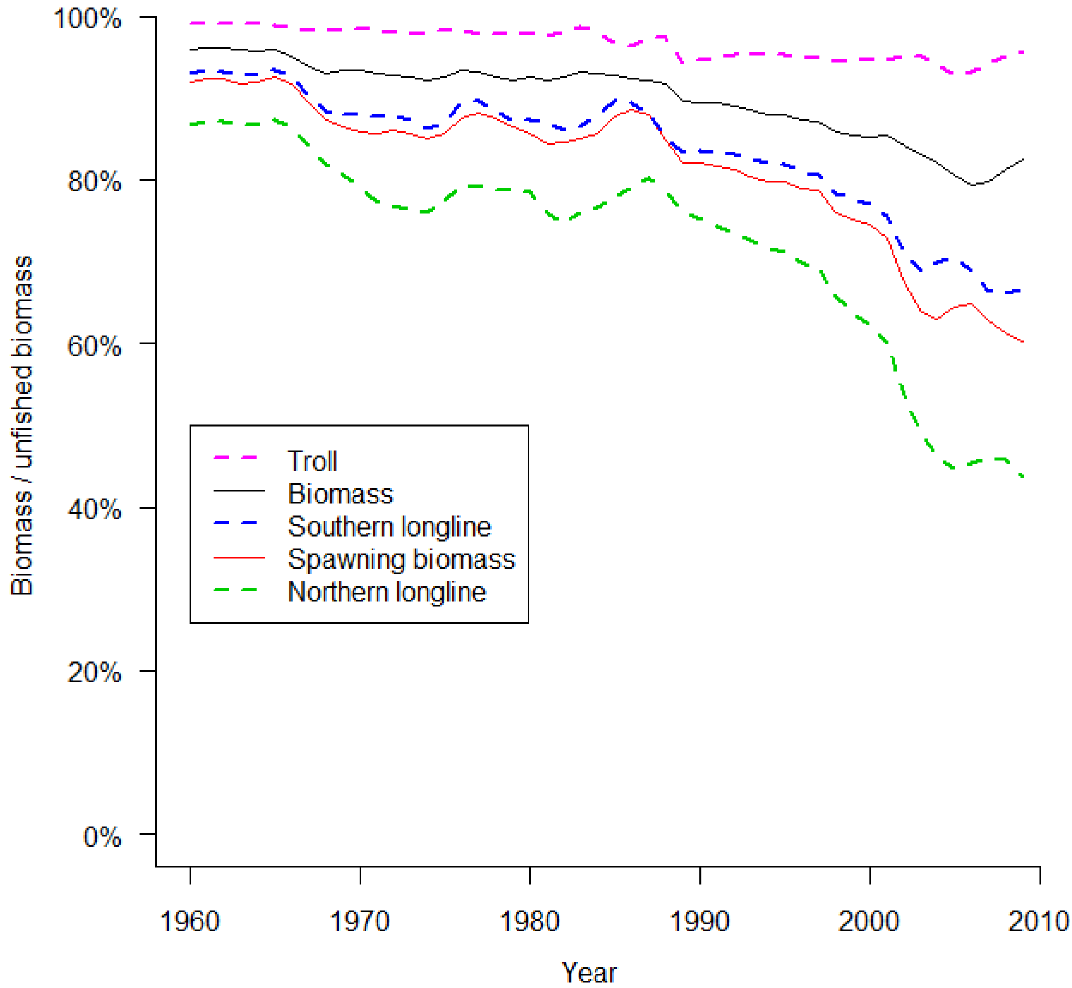

Figure 33: Decline in biomass due to the impact of fishing mortality, for exploitable biomass in the troll, southern longline, and northern longline fisheries, for total biomass and for spawning biomass.

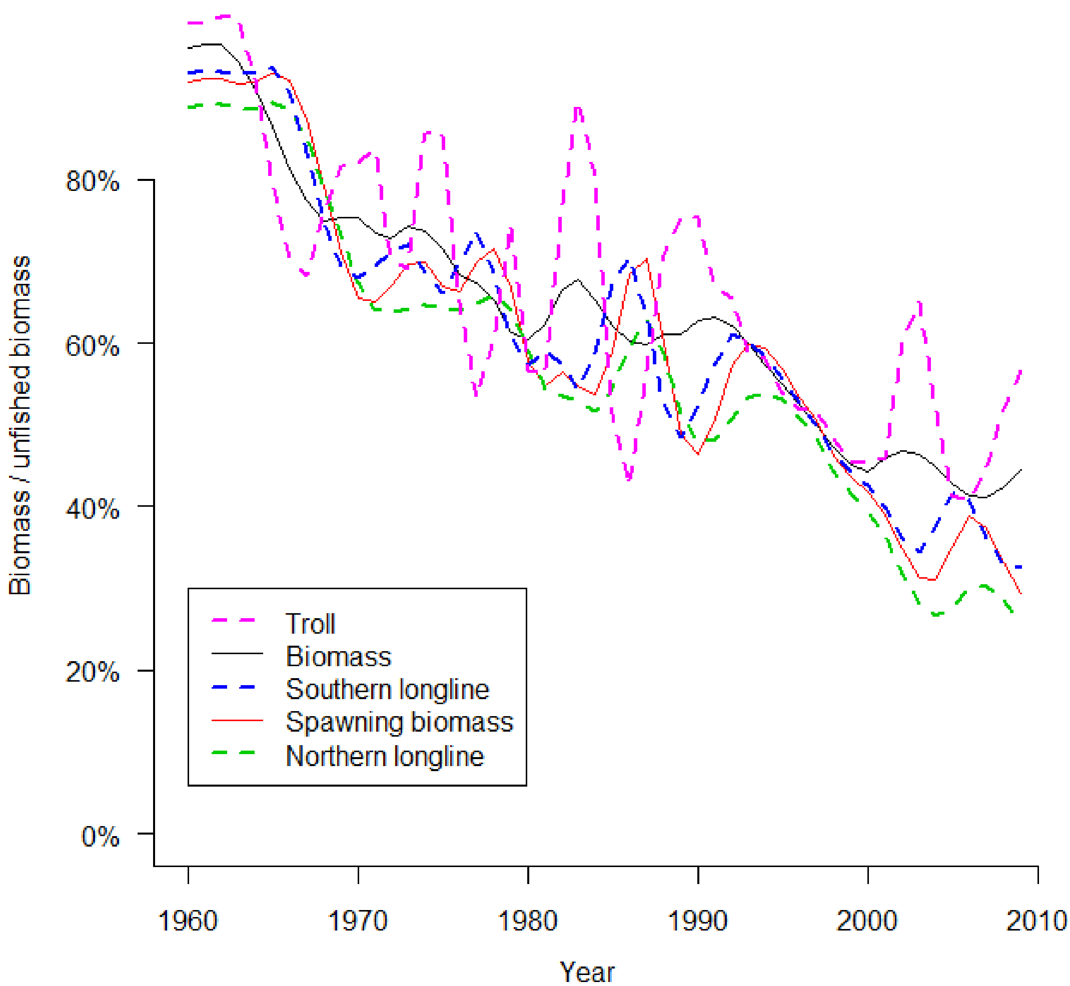

Figure 34: Decline in biomass relative to initial biomass B_0, for exploitable biomass in the troll, southern longline, and northern longline fisheries, for total biomass, and for spawning biomass.

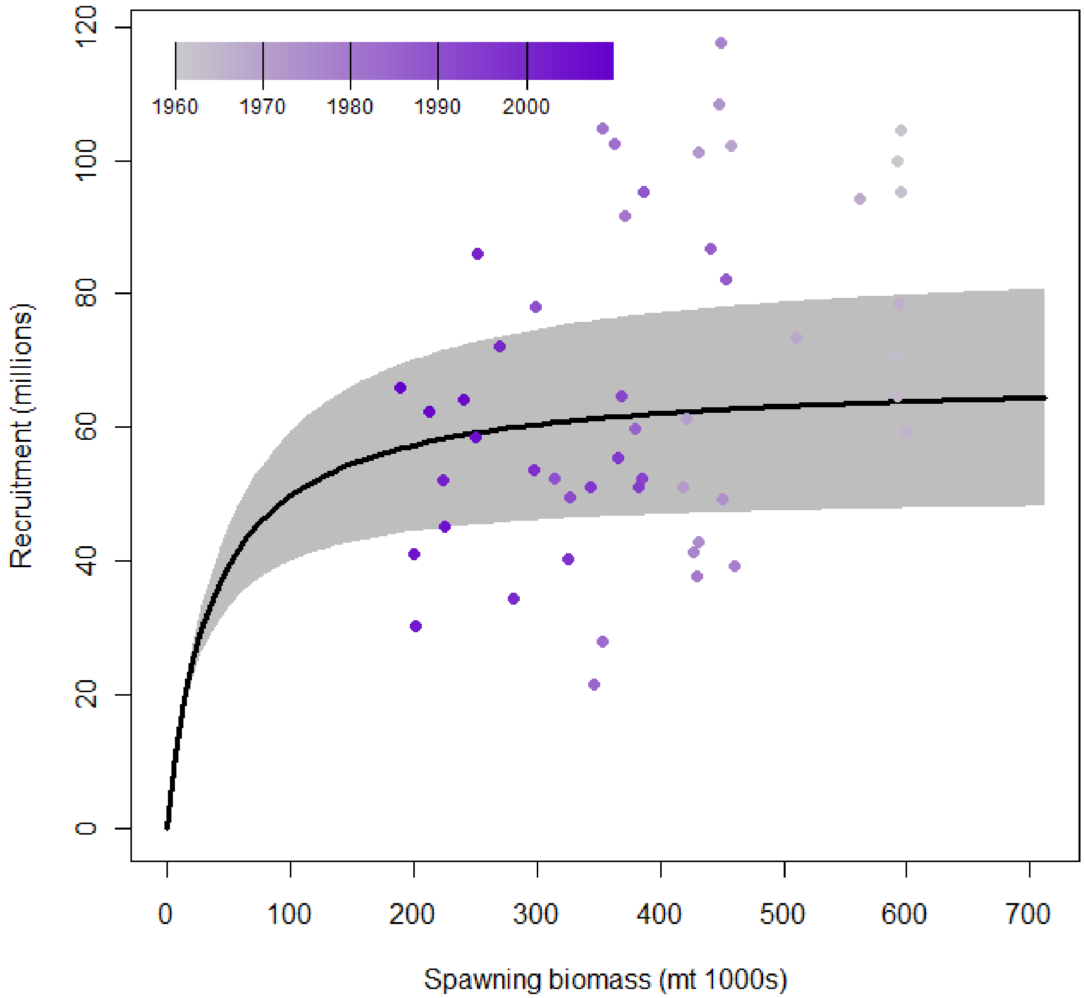

Figure 35. Spawning biomass–recruitment estimates and the fitted Beverton-Holt stock-recruitment relationship (SRR). The grey area represents parameter uncertainty estimated from the Hessian matrix.

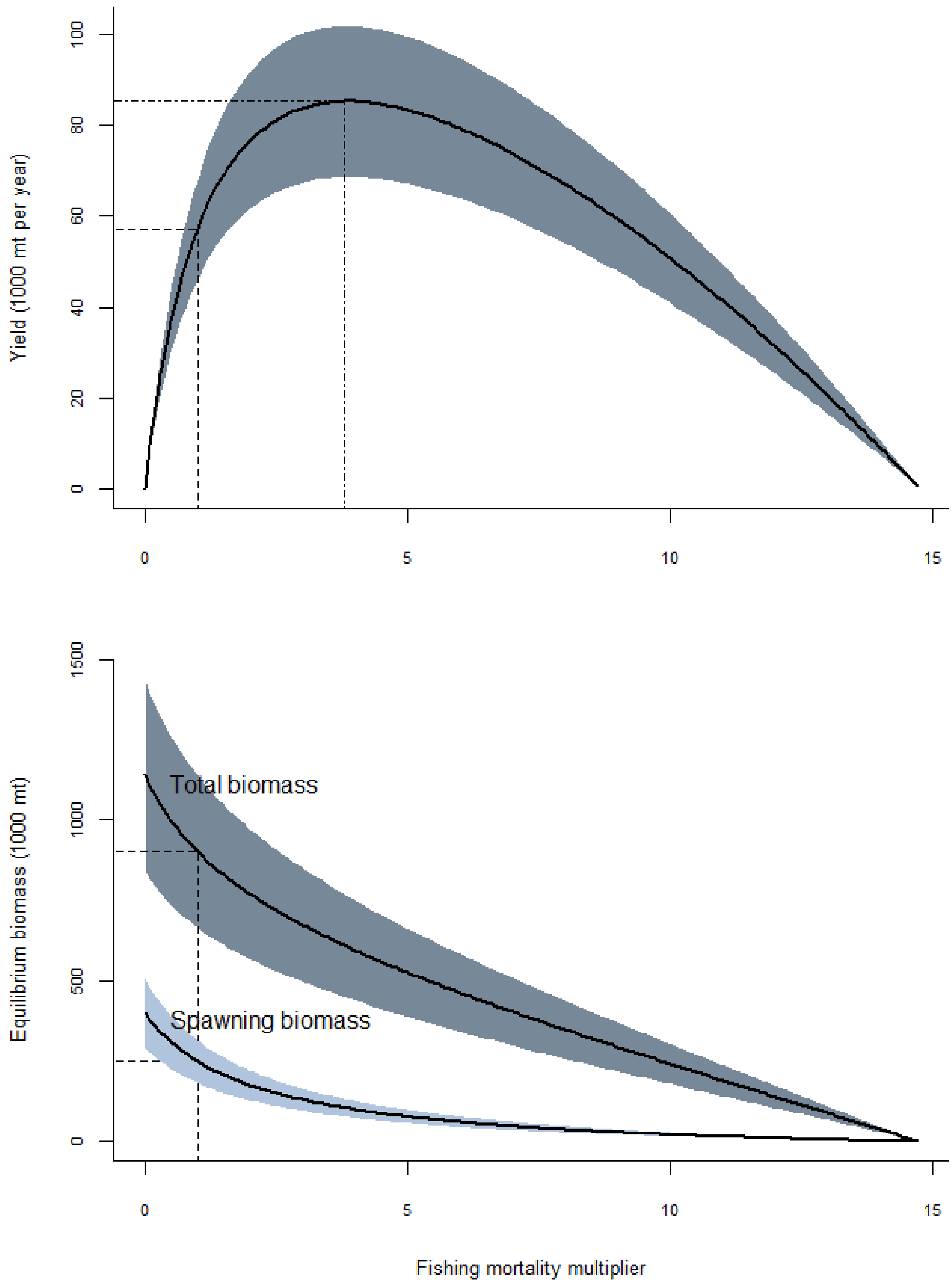

Figure 36: Yield, equilibrium biomass and equilibrium spawning biomass as a function of fishing mortality multiplier. In the top figure, dotted lines indicate equilibrium yield at the current fishing mortality, and maximum sustainable yield. In the lower figure, dotted lines represent equilibrium values of spawning biomass and total biomass at current fishing mortality. Greyed area represents uncertainty in the yield resulting from parameter uncertainty

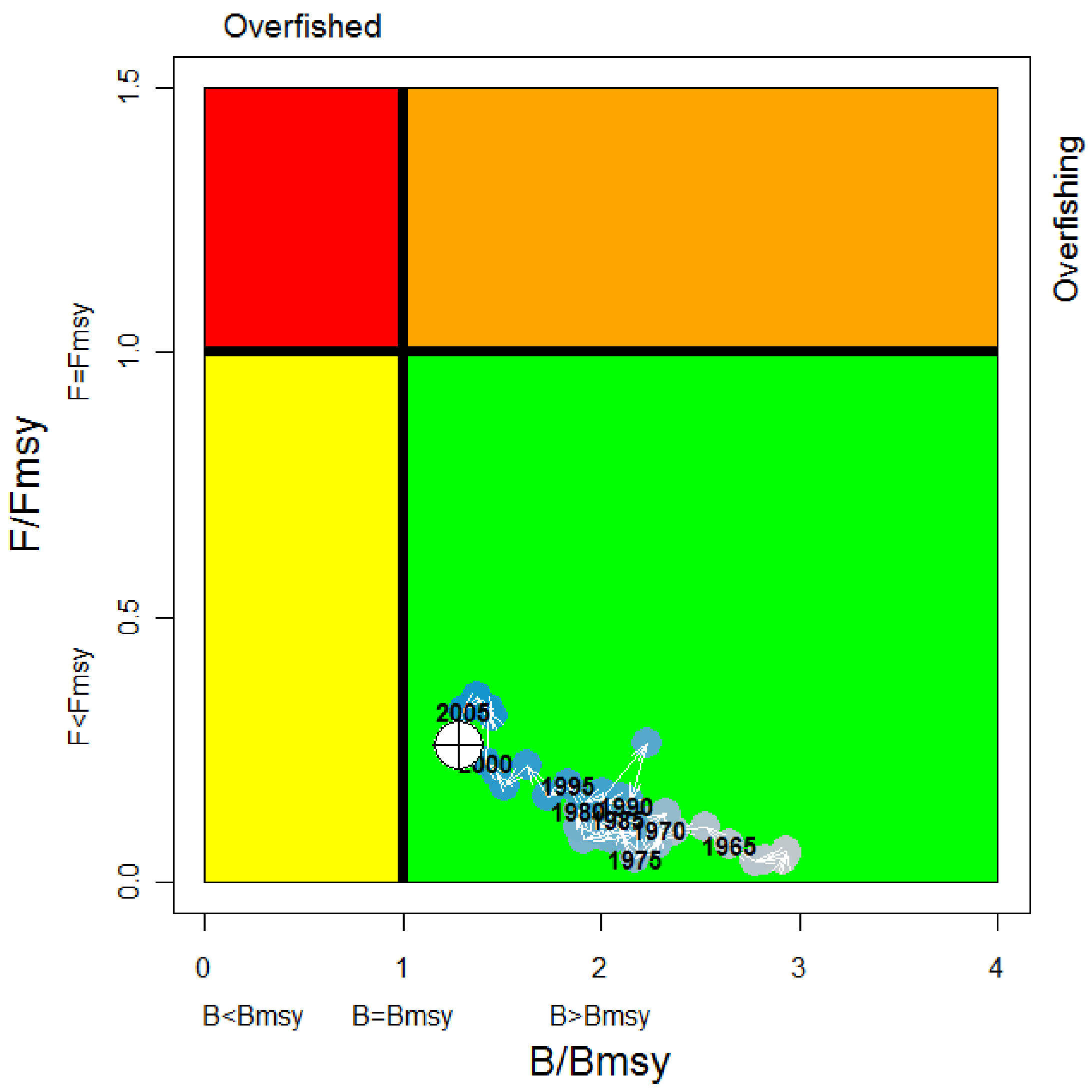

Figure 37: Temporal trend in annual stock status, relative to B_{MSY} (x-axis) and F_{MSY} (y-axis) reference points, for the model period (starting in 1960). The colour of points is graduated from pale blue (1960) to blue (2009), and points are labelled at five-year intervals. The last year of the model (2010) is excluded because it is highly uncertain.

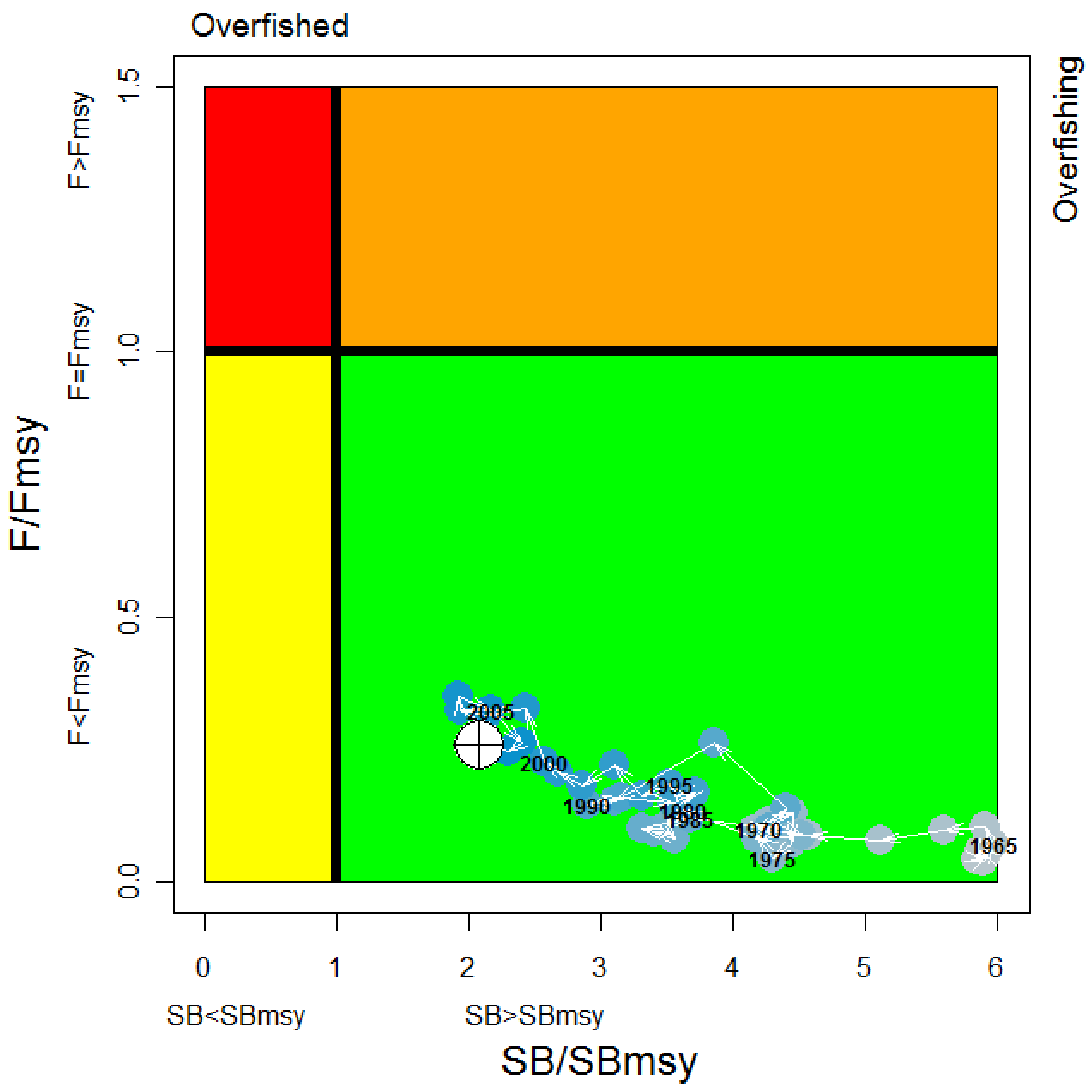

Figure 38: Temporal trend in annual stock status, relative to SB_{MSY} (x-axis) and F_{MSY} (y-axis) reference points, for the model period (starting in 1960). The colour of the points is graduated from pale blue (1960) to blue (2009), and points are labelled at five-year intervals. The last year of the model (2010) is excluded because it is highly uncertain.