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# STOCK ASSESSMENT OF ALBACORE TUNA IN THE SOUTH PACIFIC OCEAN

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## Table of Contents

## Executive Summary

1. 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 2011), 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. The model is age (20 age-classes) structured and the catch, effort, size composition and tagging data used in the model are classified by 30 fisheries and quarterly time periods from July 1960 through June 2011. The assessment included a range of model options and sensitivities that were applied to investigate key structural assumptions and sources of uncertainty in the assessment.

2. This assessment is supported by several other analyses that are documented separately, but should be considered when reviewing this assessment as they underpin many of the fundamental inputs to the models. These include standardization of longline catch and effort data to produce indices of abundance (Bigelow & Hoyle 2012), and new information about the relationship between female albacore size and reproductive output (Farley et al. 2012). In particular, new information about factors affecting albacore growth (Williams et al. 2012;Farley et al. 2012) has improved our understanding of albacore population dynamics. ,

3. The assessment includes a series of model runs describing stepwise changes from the 2011 assessment to develop a new "reference case[2]" model, and then a series of "one-off" sensitivity models that represent a single change from the reference case. The sensitivity runs were included in a structural uncertainty analysis (grid) for consideration in developing management advice.

4. The structure of the assessment model was similar to the previous (2011) assessment, but there were some substantial revisions to key data sets, specifically the longline CPUE indices, catch, and size data. There were also significant changes to biological parameters: the ogive defining spawning potential at age, and the growth curve. In addition, the assumed steepness for the reference model was increased from 0.75 to 0.8 to be consistent with other assessments; and lognormal bias adjustment was applied to the mean recruitment estimate. Cumulatively, these changes resulted in a change in the key results from the 2011 assessment, with increases in the overall level of biomass and the estimates of $MSY$, $B_{current}/B_{MSY}$ and $SB_{current}/SB_{MSY}$ Overall, the current model represents an improvement to the fit to the key data sets compared to 2011 indicating an improvement in the consistency among the main data sources, principally the longline CPUE indices and the associated length frequency data.

5. However, there continues to be conflict between the CPUE and length frequency data. The model currently includes only a single sex and the same growth curve for all locations, whereas albacore growth is now known to vary between sexes and with longitude (Williams *et al.* 2012). The model results are highly sensitive to the growth curve, so this is a key source of structural uncertainty.

6. We offer the following conclusions, which are similar to those in 2009 and 2011:

[2] While the Ref.case model run is designated the "reference case" model for the purpose of structuring the modelling analyses, the most appropriate model run(s) upon which to base management advice will be determined by the Scientific Committee.

**Stock status**

- Estimated stock status is similar to 2009 and 2011 estimates.
- The fishing mortality reference point $F_{current}/F_{MSY}$ has a median estimate of 0.21, (90% CI 0.04-1.08) and on that basis we conclude that there is low risk that overfishing is occurring. The corresponding biomass-based reference points $B_{current}/\tilde{B}_{MSY}$ and $SB_{current}/S\tilde{B}_{MSY}$ are estimated to be above 1.0 (median 1.6, 1.4-1.9, and median 2.6, 1.5-5.2 respectively), and therefore the stock is not in an overfished state.
- The median estimate of *MSY* from the structural sensitivity analysis (99,085 mt, 46-560 – 215,445) is comparable to the recent levels of (estimated) catch from the fishery ($C_{current}$ 78,664 mt, $C_{latest}$ 89,790 mt).
- There is no indication that current levels of catch are causing recruitment overfishing, particularly given the age selectivity of the fisheries.
- Longline catch rates are declining, and catches over the last 10 years have been at historically high levels and are increasing. These trends may be significant for management.
- Management quantities are extremely sensitive to the estimated growth curve. Given that biological research indicates spatial and sex-dependent variation in growth, which is not included in the model, these uncertainties should be understood when considering estimates of management parameters. .

A number of potential research directions are suggested.

- Model different growth curves both spatially and by sex within the stock assessment.
- Investigate available spatially explicit and sex-specific data on catch at age from otoliths, in order to ground-truth the model's estimates of total mortality.
- Further 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.
- Investigate alternative reference points to those based on *MSY*, which may be more relevant, precise, and stable across assessments.
- 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. Biological work to better understand fish movement patterns is desirable.

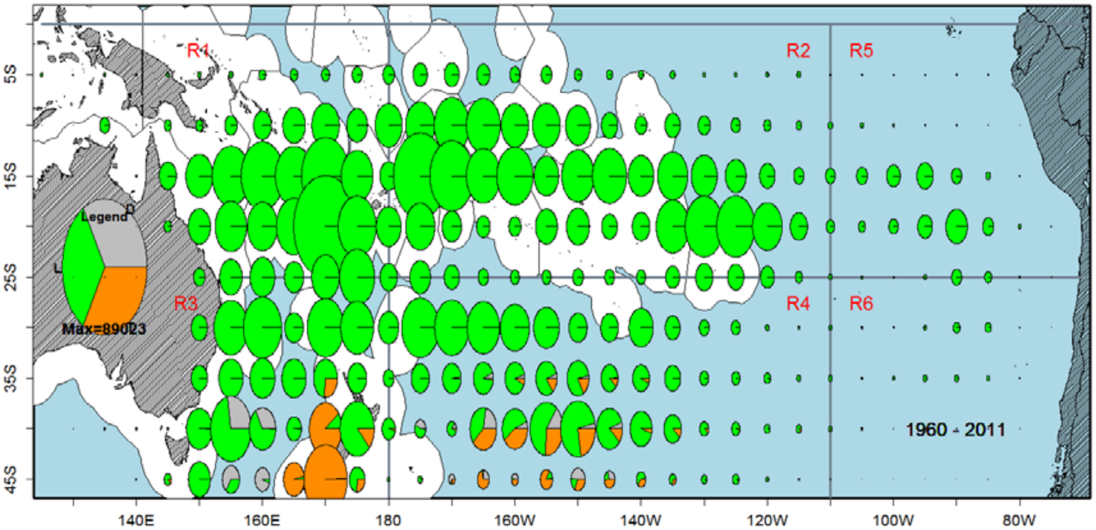


Figure ALB1: Map showing model regions 1 to 6, and the total catches (1960 to 2011) by 5° squares of latitude and longitude by the longline, troll, and driftnet fisheries.

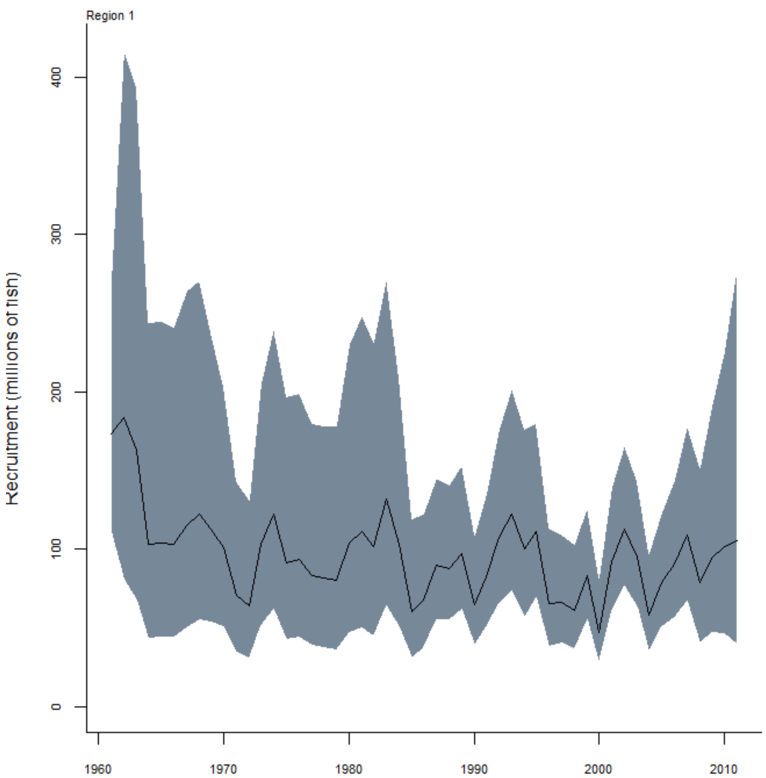


**Figure ALB2: Annual recruitment (number of fish) estimates. The grey area represents parameter uncertainty estimated from the Hessian matrix.**

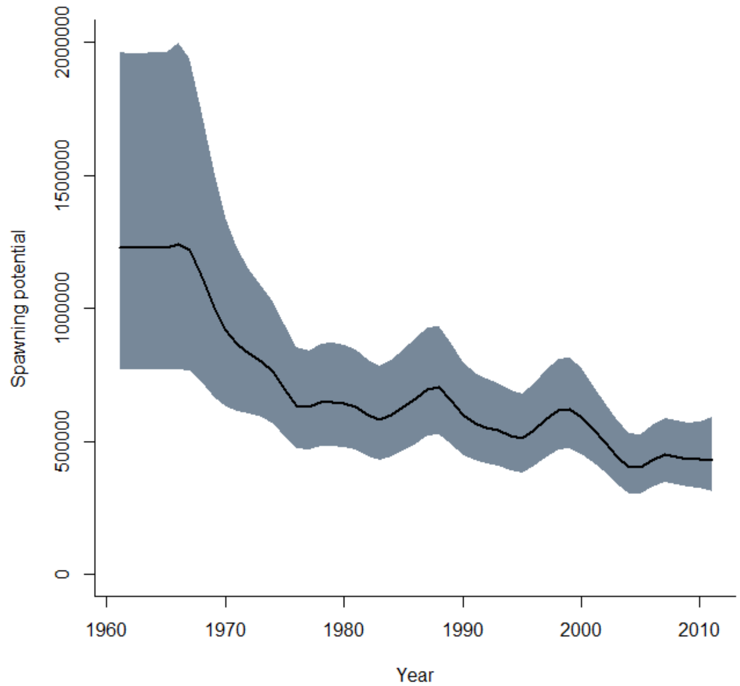


Figure ALB3: **Annual estimates of spawning potential, also referred to as adult biomass. The grey area represents parameter uncertainty estimated from the Hessian matrix.**

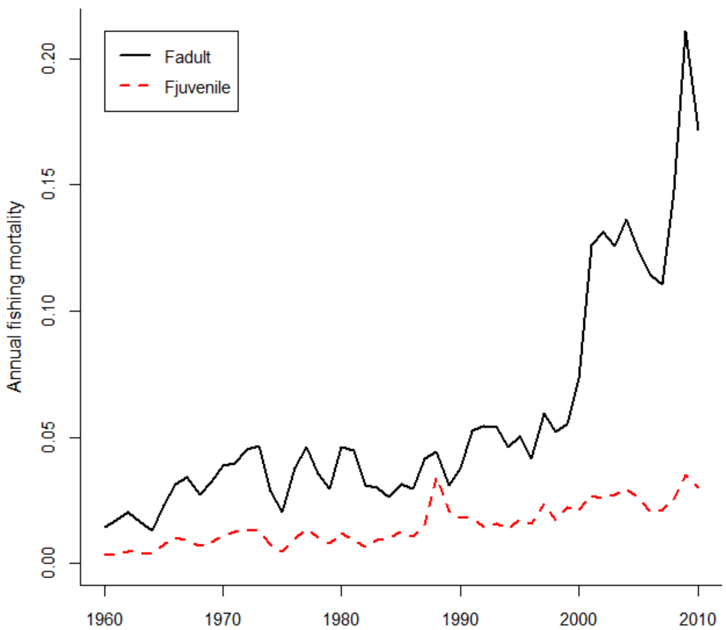


**Figure ALB4: Annual estimates of fishing mortality for juvenile and adult South Pacific albacore.**

# 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 summarize 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*) ($\mathrm{B_{current}}/\widetilde{\mathrm{B}}_{\mathrm{MSY}}$) and recent fishing mortality to fishing mortality at *MSY* ($\mathrm{F_{current}}/\tilde{\mathrm{F}}_{\mathrm{MSY}}$). 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 maximizing an objective function, consisting of both likelihood (data) and prior information components.

# 2 Background

## 2.1 Biology

Albacore tuna comprise a discrete stock in the South Pacific (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 1), 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;Farley et al. 2012). Subsequent growth is slower, at approximately 10 cm per year from ages 2–4, declining thereafter (Williams et al. 2012). Maximum recorded length is about 120 cm (FL). Recent analyses of length at age from otolith data have identified important patterns in south Pacific albacore growth curves (Williams et al. 2012;Farley et al. 2012). Males grow to larger sizes than females, and their lengths at age start to diverge above about 85cm, the length at sexual maturity (Figure 14). Lengths at age of both sexes also vary with longitude, with both growth rates and maximum sizes increasing toward the east and reaching a maximum at about 200-200° E (Figure 15).

The instantaneous 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, Chinese Taipei, and China, and the domestic longline fleets of a number of 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. Since the mid-1990's, 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, Tonga, and Vanuatu. The last few years have seen a further increase in longline catch. 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 3). 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 have varied considerably. Post-2000 they increased to over 60,000 mt, and subsequently to over 80,000 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 Territories, and a recent increase in the numbers of fish caught is also apparent in the Chinese and Chinese Taipei longline fisheries (Figure 6). Catches from the troll fishery are relatively small, generally less than 10,000 mt per year. The driftnet catch reached 22,000 mt in 1989, but has since declined to zero following a United Nations moratorium on industrial-scale drift-netting.

# 3 Data compilation

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

## 3.1 Spatial stratification

The geographic area encompassed in the assessment is the Pacific Ocean south of the equator, from 140°E to 70°W (Figure 3). This area includes all of the albacore catch from the South Pacific.

Previous stock assessments of South Pacific albacore covered the area west of 110°W, and stratified this area into three latitudinal bands (Fournier et al. 1998;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°, 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 and subsequent assessments, two changes were made to the definitions of spatial strata 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 8).

## 3.2 Temporal stratification

The time period covered by this assessment is July 1960 to June 2011. 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 2011 are limited, so for most purposes, inferences should focus on results up to 2010.

## 3.3 Definition of fisheries

MULTIFAN-CL 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 2011 assessment. In summary, 30 fisheries were initially defined, consisting of 26 separate longline fisheries, two driftnet fisheries, and two troll fisheries (Table 1). The longline fisheries comprised: i) Japanese, Korean and Chinese Taipei longline fisheries in each of the four western and central regions (i.e. accounting for 12 fisheries), ii) domestic fleets of Fiji, French Polynesia, New Caledonia, New Zealand, Samoa and American Samoa combined, and Tonga (i.e. 6 fisheries), iii) Australia’s domestic fishery in two regions (i.e. 2 fisheries), and iv) the remaining longline data from all six regions (i.e. 6 fisheries). Separate troll and driftnet fisheries were defined for the south western and south central regions of the assessment area. The geographic distribution of the cumulative catch from each fishery is presented in Figure 8.

Working from this initial model structure, further changes were made to fisheries within the model. These changes may be thought of as technical changes to the way selectivity and catchability are modelled. However, because 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°-square resolution for 1952–2011. 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 1975–2011, 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 number 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 (1967–2011). 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). 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.

For Chinese Taipei 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 2012) 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 10b and c.

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°-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 1993–2011 have been aggregated and raised according to annual catch estimates.

**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 in this region 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

In previous years there have been standardised CPUE indices for each region for the three DWFN fleets. This year the indices were replaced with a single index for each region, estimated from available longline catch and effort logbook data for all vessels thought to be targeting albacore (details in Bigelow & Hoyle 2012). The indices are applied to the Taiwanese longline fisheries, which are the fisheries covering the broadest area for the longest period. The indices are generally consistent with one another (Figure 10a), but there is some variation in the initial period of decline and the overall magnitude of the decline. This variation is largely consistent with the fact that the sizes of captured albacore tend to be larger to the north of 25S, and also to increase from east to west. Larger fish have usually been exposed to fishing mortality for longer, and so the abundance of older, larger fish is more affected by fishing pressure than is the abundance of younger smaller fish.

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 their CPUE trends can be 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). 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. Data for the period since 2003 have been provided by Chinese Taipei.

**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 several 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.

Additional processing was applied to size data for longline fisheries in order to improve their consistency through time. Conflicting information in the length frequency data and the CPUE time series have long been a feature of the south Pacific albacore stock assessment. A new approach was taken in this assessment in order to reduce the conflict, similar to that used in the 2011 bigeye and yellowfin stock assessments (Hoyle & Langley 2011).

The sizes of albacore caught in the longline fisheries show considerable spatial variation, even within fisheries and regions. In some fisheries, there are medium to long-term trends in size data across sampling locations, which cause trends in observed sizes. In MULTIFAN-CL, size data within a fishery are assumed to be sampled with constant selectivity, so such size trends in the observed data imply equivalent size trends in the population, which is not the case.

To address this problem, size data were reweighted according to the proportion of catch taken within each 10°x20° area, averaged over the period of the stock assessment. Size data from areas with more catch in a fishery therefore received more statistical weight than samples from areas less heavily fished by that fishery. For time periods during which size data for a fishery was only available from areas that on average took less than 30% of that fishery's catch, the size data were removed.

## 3.6 Tagging data

Limited tagging data were available for incorporation into the MULTIFAN-CL 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 12). 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 MULTIFAN-CL 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 13). 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 13). The Chinese Taipei longline fishery in Region 2 also accounted for a relatively high proportion of all tag returns (20%). A few tags were also returned from the two troll fisheries. Most tag recoveries occurred during the five years following the peak in releases (i.e. the early 1990s) (Figure 12).

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. They were re-calculated for this assessment, based on analyses of biological data (Ashley Williams personal communication) collected during an SPC-CSIRO project (Farley *et al.* 2012) and following the method used for the 2008 albacore stock assessment (Hoyle 2008), and also applied to bigeye (Hoyle & Nicol 2008) and yellowfin (Hoyle et al 2009) tunas in the WCPO. The resulting ogive is on the relative reproductive potential of females rather than the relative biomass of both sexes above the age of female maturity. 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 per spawning at age of mature females.

Analyses for the previous assessment assumed increased natural mortality of females above the age of maturity. It was assumed that the proportions of females at age decline with increasing age, as they do with increasing length. However, it has recently been demonstrated that females grow to a significantly smaller size than males (Williams *et al.* 2012), which may by itself be sufficient to explain the observed changes in sex ratio with increasing length. We have therefore assumed that natural mortality at age is constant and the same for both sexes, and that sex ratio does not change with age.

Overall, these combined changes result in a moderate shift in the reproductive potential ogive to the left, and a substantial increase in the reproductive potential for older age classes relative to the values used in the 2011 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, but subsequently estimated within the model. The data that provide by far the most information about growth rates is the New Zealand troll data, mostly sampled from 165-175°E, which is modelled at a monthly time step and demonstrates very clear and consistent growth modes. Growth rates of the fish sampled in this fishery may be slower than the population average, since growth rates at 165-175° are estimated to be relatively slow (Williams *et al.* 2012). Several sensitivity analyses to alternative growth parameters were considered by fixing the growth curve at faster growth rates.

Natural mortality (*M*) at age is assumed to be a constant value of 0.4 for both sexes (Figure 16), and time-invariant. Alternative natural mortality rates of 0.3 and 0.5 are considered as sensitivity analyses.

# 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

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.

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 for the Fijian and French Polynesian fleets, and a divisor of 40 was applied.

### 4.1.3 Tagging data

A log-likelihood component for tagging data was computed using a Poisson distribution, consistent with 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 from immediate mortality due to tagging and from tag shedding.

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 MULTIFAN-CL 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 a recruitment of about three times the average recruitment would occur about once every 20 years, on average.

Recruitment was assumed to be related to spawning potential 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 0.8, with *S* defined as the ratio of the equilibrium recruitment produced by 20% of the equilibrium unexploited spawning potential to that produced by the equilibrium unexploited spawning potential (Francis 1992;Maunder *et al.* 2003). In other words, the prior belief is that when the equilibrium spawning potential is reduced to 20% of its unexploited level, equilibrium recruitment would be reduced to 80% of its unexploited level. The 2011 assessment assumed steepness of 0.75, but the change was made this year to be consistent with the bigeye, yellowfin, and skipjack assessments. Steepness values of 0.65 and 0.95 were considered as sensitivity analyses, and as part of the grid.

## 4.4 Age and growth

Age and growth assumptions in the MULTIFAN-CL 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 distributions is more important, given the relative importance of length-frequency data in the total log-likelihood function.

All longline fisheries were split into four each year (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). MULTIFAN-CL does not have the facility to vary selectivity through time within a fishery, since it is constrained to be constant.

For the 2009, 2011 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, apart from the Chinese Taipei fisheries which were assumed to have constant catchability. Fishery splits were applied in 1977 to the Chinese Taipei 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 Chinese Taipei 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 the Chinese Taipei fleets. This assumption was based on the fact that CPUE for these fisheries was derived from the standardisation of data from vessels estimated to be targeting albacore (Bigelow & Hoyle 2012).

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 annually, 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 improving technology on existing vessels. A sensitivity analysis for effort creep was carried out, with fishing power increasing at the rate of 0.5% per year.

## 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 2012). This resulted in more weight being given to the indices from regions 1 and 2.

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).

Penalties on effort deviates before 1975 were reduced substantially to allow biomass to decline more slowly than the CPUE trend. An alternative scenario with the standard penalty weights on early CPUE was run as a sensitivity analysis and included in the grid.

## 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. Scenarios with natural mortality of 0.3 and 0.5 were run as sensitivity analyses and included in the structural sensitivity analysis grid.

Unlike the 2008-2011 assessments, natural mortality was assumed to be constant through time. See the paragraph in Section 3.7 on sex-dependent growth and sex ratios for a discussion of this issue.

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 on management parameters.

## 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 *et al.* (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

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, and *h* which is fixed at a predetermined level, 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. The 'current' period is defined as the last four years in the model, but omitting the most recent year because it is too uncertain.

## 4.12 Alternative structural scenarios

A set of sensitivity analyses was run to examine the effects of alternative structural scenarios. We also used these analyses to estimate the size of the uncertainty associated with assumptions about the model structure. All scenarios were modelled both individually and in a structural uncertainty analysis, with all possible combinations of each set of factors. See also Table 4.

- steepness parameter of 0.65, 0.8, and 0.95;
- growth curve estimated, or fixed at one of 6 alternative growth curves. The alternative curves involved the quantities Kdiff and Ldiff, derived from the longitudinal growth variation observed in growth curves from otoliths (Table 5 in Williams *et al.* 2012). $K_{diff}=((K_{longitude=220°} + K_{185°})-2*K_{155°})/2$, averaged across male and female growth curves. Ldiff was the equivalent quantity for $L\infty$.

1. $K = K_{base} + K_{diff}$, $L_{max} = L_{max\_base} + L_{diff}$
2. $K = K_{base} + K_{diff}/2$, $L_{max} = L_{max\_base} + L_{diff}/2$
3. $K = K_{base} + K_{diff}$, $L_{max} = L_{max\_base}$
4. $K = K_{base} + K_{diff}/2$, $L_{max} = L_{max\_base}$
5. $K = K_{base} + K_{diff}$, $L_{max}$ = estimated
6. $K = K_{base} + K_{diff}/2$, $L_{max}$ = estimated

- no effort creep, or 0.5% effort creep per year;
- mean natural mortality of 0.3, 0.4, or 0.5;
- CPUE data included for all four regions, for the western regions 1 and 3 only, or for the eastern regions 2 and 4 only;
- CPUE before 1975 either down-weighted as in the reference case, or given the weights estimated in the CPUE standardization.

### 4.13 Summary of changes since last assessment

The main changes to the base-case model since the 2011 assessment to get to the 2012 reference case model were:

- The version of MULTIFAN-CL was updated.
- The number of function evaluations in the next-to-last phase was increased in order to better estimate the growth curve and selectivities.
- The catch, effort, and length frequency data were updated.
- Length frequency data from the Chinese Taipei distant water longline fishery after 2003 were added.
- A higher value of steepness (0.8 rather than 0.75) was assumed.
- A new time series of single standardized CPUE per region, based on all albacore-targeted longline effort in that region, was applied to the Chinese Taipei longline fishery. In previous assessments separate indices were estimated for the Japanese, Korean, and Chinese Taipei distant water longline fisheries.
- Interpretation of the standardized CPUE indices was changed by removing catchability deviates and reducing the penalty weights on effort deviates before 1975. This is effectively a different implementation of the same principle, but in practice less weight was given to the early CPUE data.
- The natural mortality-at-age ogive was changed to reflect the assumption that both sexes have the same natural mortality.
- Sex ratio at age in the spawning potential ogive was changed to reflect, as above, the assumption that both sexes have the same natural mortality.
- The spawning potential at age ogive was changed based on new estimates of maturity, spawning fraction, and fecundity from biological sampling of south Pacific albacore.
- Size data samples were re-stratified to match the long-term spatial distribution of the catch within each longline fishery. This was done to reduce bias due to movement of sampling locations through time.
- *MSY* calculations were adjusted for lognormal bias, using a new feature of MULTIFAN-CL.

## 5 Results

This section presents results for the reference case model and a structural sensitivity analysis grid. The results and diagnostics of the reference case are presented in detail, including yield estimates and performance indicators. However, median estimates from the grid may be considered by the scientific committee to be the most representative management parameters.

## 5.1 Model changes

The effects of the changes described below are displayed in a series of figures for spawning potential (Figure 18), total biomass (Figure 19), and recruitment (Figure 20) through time. Likelihoods and estimates of management and growth curve parameters are presented in Table 8.

### 5.1.1 New MULTIFAN-CL and longer growth estimation phase

The new version of MULTIFAN-CL gave a very similar result. Increasing the length of the growth estimation phase resulted in more stable and consistent growth estimates. There was a slight increase from the 2011 estimate, reflecting small differences between the growth curves.

### 5.1.2 Add catch and effort data

Addition of new catch and effort data resulted in a moderate increase to the biomass. The new data included significant increases in catch, including some catches during periods included in the previous assessment. The higher catch may have required a larger biomass in order to be consistent with the observed CPUE trend.

### 5.1.3 Add length frequency data

Adding the new length frequency data further increased the estimated biomass levels. Adding the length frequency data changed the growth curve and the selectivity estimates, increasing the variability of length at age. Some quite large fish in the recent Chinese Taipei length frequency data may have been influential.

### 5.1.4 Steepness 0.8

Changing the assumed steepness estimate did not affect the biomass or recruitment trends, but increased the *MSY* estimate by about 8%.

### 5.1.5 New CPUE series

The trend in the new CPUE time series is different from the previous approach, with less decline during much of the time series, but a steeper decline during the early period. The biomass trend changed to reflect these differences.

### 5.1.6 Early CPUE modelling approach

The new approach to the early CPUE changed the trend during this period, but had little effect on biomass after the mid-1970’s. There was also little effect on management parameters.

### 5.1.7 M ogive

Changing the natural mortality at age ogive had very little effect on biomass trends, but slightly increased recruitment estimates.

### 5.1.8 Sex ratio at age

Changing the sex ratio at age gave more influence to older fish in the population, but given their low numbers had relatively little effect on spawning potential.

### 5.1.9 Spawning potential at age

Changing the spawning potential at age increased the contribution of younger fish, and so increased the overall spawning potential. It had no effect on total biomass or recruitment estimates.

### 5.1.10 Size data restratification

Restratifying the size data changed the growth curve and selectivities, and resulted in a steeper decline in the population biomass trend.

### 5.1.11 Lognormal bias adjustment

The lognormal bias adjustment has its effect via the stock recruitment relationship and does not significantly affect the population trend. There was a small effect on early recruitments, reflecting both uncertainty about these recruitment estimates and the effects of the recruitment deviation penalty. The *MSY* increased by about 4%.

## *5.2 Sensitivity to alternative assumptions*

All models are based on assumptions. In many cases the 'right' assumption is not known, so it is important to measure the effects of choosing other plausible assumptions. We ran the base case model with several alternative assumptions, which we considered to be as plausible as the base case. The effects of these alternatives are shown in a series of figures showing spawning potential (Figure 21), total biomass (Figure 22), and recruitment (Figure 23) through time. Likelihoods and estimates of management and growth curve parameters are presented in Table 8.

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

- steepness parameter of 0.65, 0.8, and 0.95;
- growth curve estimated, or fixed at one of 2 alternative growth curves (both with faster growth);
- no effort creep, or 0.5% effort creep per year;
- mean natural mortality of 0.3, 0.4, or 0.5;
- CPUE data included for all four regions, for the western regions 1 and 3 only, or for the eastern regions 2 and 4 only;
- CPUE before 1975 either down-weighted as in the reference case, or given the weights estimated in the CPUE standardization.

### 5.2.1 Steepness = 0.65, 0.8, 0.95

Varying the assumed steepness had, as expected, little effect on population dynamics or model fit, but considerable impact on *MSY*-related parameters. Both higher and lower values of steepness resulted in marginally lower early biomass estimates. Lower values of steepness resulted in more pessimistic stock status, and higher values more optimistic stock status. All three options were included in the structural sensitivity analysis grid.

### 5.2.2 Growth curve option

Growth curves fixed at levels closer to those seen further east resulted in very significant changes to recruitment, biomass, and management parameters. The changes that increased *Lmax* or the sizes of adult fish resulted in worse stock status with respect to $F/F_{MSY}$ and $SB/SB_{MSY}$ in particular, while changes that resulted in lower *Lmax* tended to result in higher *MSY* estimates and more optimistic stock status. The run 'Alt growth 1' resulted in unrealistically high fishing mortality, so was not included in the structural sensitivity analysis grid. The 2 runs 'Alt growth 5' and 'Alt growth 6' estimated lower *Lmax* and lengths at age for most adult albacore, when the aim of the exercise was to consider alternate faster-growing growth curves. It was considered reasonable to include one fully-weighted run with this growth pattern, rather than 2, so 'Alt growth 5' was not included in the structural sensitivity analysis grid.

### 5.2.3 Effort creep 0.5%

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

### 5.2.4 Mean M = 0.3, 0.4, 0.5

Higher natural mortality of 0.5 produced higher recruitment and a moderate increase in biomass, but given the older age structure, spawning potential was about the same as the scenario where M was equal to 0.4. With lower M recruitment was lower and biomass was similar to the base level M=0.4, but spawning potential increased. Lower natural mortality implies a less productive stock, and stock assessment outcomes were somewhat less optimistic. All three options were included in the structural sensitivity analysis grid.

### 5.2.5 CPUE time series

The CPUE time series had a moderate effect on biomass trends but little effect on management parameters. The CPUE time series from western regions showed less decline than the series from the east, and as a result the recruitment and biomass time series were more stable. Use of the CPUE time series from the east resulted in a similar trend to the base case, reflecting the fact that the eastern estimates are more precise and therefore have more influence on the assessment. Use of the western indices improved the stock status with respect to $B_{MSY}$ and $SB_{MSY}$, but had little effect on $F/F_{MSY}$. All three options were included in the structural sensitivity analysis grid.

### 5.2.6 Nominal weight on early CPUE

Increasing the penalty weights on the early data to nominal levels resulted in slight steeper declines in the early biomass time series, but had negligible effects on management parameters. Both options were included in the structural sensitivity analysis grid.

## 5.3 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 and CPUE data. The following observations are made concerning the various fit diagnostics:

- The log total catch residuals by fishery (Figure 24) are relatively small, since large penalties constrain the estimated catch to be close to the observed catch. 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. Where the deviates for these LL fisheries are close to zero for a period, this relates to missing effort data, so the catch can be fitted exactly.

- The model predicts the number of tag recoveries from the population at each time interval (Figure 25). 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 26). 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 27). 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 (65%). This largely reflects the fact that the tags were released in regions 3 and 4. Mixing across the whole region is assumed, but this is probably not realistic.

- 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 28), 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 29), and in plots of exploitable biomass versus observed CPUE (Figure 30). 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. The most significant trends occur in the effort deviates before 1975 in the Chinese Taipei, Japanese and Korean longline fisheries. These reflect the low weight given to the effort deviates during this period.

- The estimated exploitable biomass for each fishery can be compared with individual observations of catch and effort (scaled by catchability) from the fisheries (Figure 30). 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.

## 5.4 Model parameter estimates

### 5.4.1 Catchability

Annual catchability for standardised fisheries was held constant (Figure 31). Strong temporal declines in catchability are evident in non-standardized fisheries. 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 31). 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.

### 5.4.2 Selectivity

Selectivities for longline fisheries reveal some consistent seasonal patterns (Figure 32). 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.

### 5.4.3 Growth

The estimated growth curve is shown in Figure 33, along with the alternative models run in the sensitivity analyses. As in past assessment the estimated curve is close to the average of the otolith-based length at age estimates (Williams *et al.* 2012;Farley & Clear 2008), but with slower growth initially. This may occur because of bias in the age-based growth estimates. The longline fisheries that were the source of many of the ageing samples are very size selective, so the youngest fish sampled tend to be faster-growing than the population average.

The estimated variability of length-at-age increases with age, and is moderately large for older age classes. Some of this is true variability, and some is 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.

## 5.5 Stock assessment results

Results for the reference case model are presented below.

### 5.5.1 Recruitment

Recruitment trends are less evident than in previous assessments, but there is still a general declining trend which helps drive the biomass trend (Figure 34). The initial declines in recruitment represent the model's attempt to fit a steeper decline in longline fisheries' CPUE than can be explained by the reported catch. Recent recruitment is estimated to be increasing, but is highly uncertain.

### 5.5.2 Biomass

Biomass is highly uncertain at the start of the 1960s (Figure 35 and Figure 36), and depends on the assumptions made about the early steep decline in catch rates. The estimated rate of decline depends on the weight given to the early CPUE trends, and assumptions about catchability trends before the mid-1970's. The CPUE and length frequency data, under the current model structure, provide different information about early biomass trends, with the size data suggesting a biomass increase and the CPUE data suggesting a steep decline. The implication of the size data is counter-intuitive given that catch increased substantially between 1960 and 1970 (Figure 5), but the biomass decline implied by the CPUE data is too steep to be explained by the catch.

It is not good practise to include two incompatible sources of information in a model, since one must be incorrect (Schnute & Hilborn 1993). It is also good practice to give more weight to CPUE data (Francis 2011), because the abundance information in CPUE data is more reliable than that in size data. In this assessment we have therefore included only scenarios with low weight on size data in the final phase, allowing the model to follow the trend in the CPUE data. Two scenarios are included for weight given to the early CPUE data. The reference case gives low weight to early CPUE data, with large CV's on the effort deviates. The alternate case gives the weight estimated in the CPUE standardization. In the alternate case with higher weight on the early CPUE, biomass declines more steeply than in the reference case.

The biomass trend since 1975 is fairly consistent among the different CPUE scenarios. It is relatively stable until the mid-1990s, and declines after this as total catches increase to twice their previous level. A small increase occurs in biomass in the last few years, explained by several recent years of high recruitment, but given the high recent catches spawning potential has not increased. The most recent increases in catch have not yet affected the biomass trend substantially.

Biomass and spawning potential levels are estimated to be close to equilibrium unfished levels until about 1990 (Figure 37), due to above average recruitment early in the time series.

### 5.5.3 Fishing mortality

Fishing mortality (exploitation) rates for adult albacore are moderately low from the early 1970s to the mid-1990's, and increase substantially since that time for adult fish (Figure 38). Estimated exploitation rates have increased since 2000 in response to higher catches (Figure 5 to Figure 7) and the lower levels of adult biomass represented by the declining 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, since troll effort has not increased.

Estimated fishing mortalities for the fully recruited age classes have reached moderate levels since 2006, averaging about 0.20 for adults in the peak year 2010 (Figure 38), and averaging about 0.25 for fully recruited age classes (Figure 39). The rate is lower for adults because not all adults are fully recruited. Estimates of fishing mortality are highly dependent on the absolute biomass estimate, which is quite uncertain. By way of comparison, annual fishing mortalities on adult bigeye tuna are estimated at approximately 0.2 (Davies *et al.* 2011).

### 5.5.4 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 of fishing can be expressed either as the depletion of exploited biomass $(1 - B_t / B_{t,F=0})$, where an unexploited stock experiences 0% depletion, or conversely as the proportion of unfished levels (biomass / unfished biomass), where an unfished stock is at 100% of unfished levels.

Impact is calculated for different components of the stock: juveniles, spawning potential, 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. The stock is estimated to be currently (average of July 2007 - June 2010) depleted by about 10% to 60% from unfished levels, depending on the fishery (i.e. longline-vulnerable biomass is between 40% and 90% of unfished levels) (Table 9, Figure 41). The current impact level on the component of the stock vulnerable to troll 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 fisheries, 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. For similar reasons, the impact is greater in the eastern regions which have larger fish (regions 2 and 4) than in the west (regions 1 and 3). Impacts also vary seasonally, with more effect in the seasons when larger fish are taken (Figure 41). The difference between north and south longline fisheries is apparent in Figure 42, which averages the effects across multiple fisheries.

Comparing the estimated impact of fishing on biomass (Figure 42) with the overall estimated biomass decline relative to initial biomass (Figure 43) demonstrates the degree to which the model is using recruitment to produce estimated biomass trends.

### 5.5.5 Yield analysis

Symbols used in the following discussion are defined in Table 7. Yield analyses conducted in this assessment incorporate the stock recruitment relationship (SRR) (Figure 45) into equilibrium biomass and yield computations. The assumed reference case steepness coefficient of the SRR is 0.8, indicating a relatively weak relationship between stock and recruitment. Equilibrium yield and total biomass in the reference case, as functions of multiples of the current (July 2007-June 2010) average fishing mortality-at-age, (*Fmult)* are shown in Figure 46a.

We suggest use of the uncertainty grid for management advice, in order to take the distribution of the uncertainty into account (Table 10). Median estimates and the 5$^{th}$ and 95$^{th}$ percentiles are presented below. Results from the reference case do not sit in the middle of the estimates from the uncertainty grid. Figure 46b is the equivalent figure to Figure 46a, but based on the structural sensitivity analysis rather than the reference case. The lines in this figure, which are based on median estimates, are not smooth due to the variability among scenarios. Also note that the median *MSY*, shown on the figure with a bold dashed line, is slightly higher than the maximum of the median sustainable yields.

Yield is maximised at *Fmult* = 4.8 (90% range of 0.9-22.7) for an *MSY* of 99,100 mt (46,600-215,400) per year. This implies that the ratio $F_{current}/\tilde{F}_{MSY}$ *is* approximately 0.21 (0.044-1.08). The equilibrium biomass at *MSY* is estimated at 587,000 mt (286,500-1,300,000), approximately 51% (44%-55%) of the equilibrium unexploited biomass ($B_{MSY}/B_0$). Spawning potential (reproductive potential) at *MSY* ($SB_{MSY}$) is estimated to be 23% (12-30%) of the unfished level ($SB_{MSY}/SB_0$).

### 5.5.6 Stock assessment conclusions

Various quantities of potential management interest associated with the yield analyses are provided in Table 9 and Table 10. Absolute quantities are provided in the top half of each table, while the bottom half contains ratios of various biomass and fishing mortality measures that might be useful for stock monitoring purposes. It is useful to distinguish three different types of ratio: i) ratios that compare a measure for a particular time period with the corresponding equilibrium measure; ii) ratios that compare two equilibrium measures (rows shaded grey); and iii) ratios that compare two measures pertaining to the same time period (row shaded black). Several commonly used reference points, such as $SB_{current}/\widetilde{SB}_{MSY}$, $B_{current}/\tilde{B}_{MSY}$, and $F_{current}/\tilde{F}_{MSY}$ fall into the first category. These ratios are usually subject to greater variability than the second category of ratios because recruitment variability is present in the numerator but not in the denominator. Category ii ratios are more robust than those in category i.

The ratios $B_{current}/B_{current,F=0}$ and $SB_{current}/SB_{current,F=0}$ can provide an indication of population depletion and fishing impact by the fisheries. Total biomass is estimated to have been depleted by fishing to approximately 0.82 (0.62-0.93) of the level it would have been if left unfished. Similarly, spawning potential is at 0.63 (0.35-0.80) (i.e. spawning potential reduced by 37% due to the impact of fishing). These represent a moderate level of depletion, above the equivalent equilibrium-based limit reference points $B_{MSY}/B_0$ and $SB_{MSY}/SB_0$.

Other reference points useful in indicating the current stock status are $\tilde{B}_{F_{current}}/\tilde{B}_{MSY}$ (1.49, 0.96-1.81) and $\widetilde{SB}_{F_{current}}/\widetilde{SB}_{MSY}$ (2.4, 0.94-5.3). Together with the yield-based reference point $Y_{F_{current}}/MSY$ (0.7, 0.37-0.99), these suggest potential to expand long-term yields from the fishery at the current pattern of age-specific selectivity, at least in terms of the productivity of the stock. However, higher fishing mortality would further reduce biomass levels and hence lower the catch rates, particularly in fisheries that catch large albacore.

Current catches (average of July 2007- June 2010) of 79,000 mt are estimated to be close to $MSY$ (99,000mt, 46,600-215,000 mt).This is possible in the short term because current biomass (1,029,000 mt, 455,000-2,047,000 mt) is estimated to be well above its equilibrium level at the current level of fishing pressure ($B_{F_{current}}$ of 909,300 mt, 302,000 mt -2,217,000 mt). Equilibrium yield at current fishing pressure ($Y_{F_{current}}$) is estimated to be 66,255 mt (46,300 mt – 85,500 mt).

The ratios $F_{current}/\tilde{F}_{MSY}$ (0.21, 0.04-1.08), $SB_{current}/\widetilde{SB}_{MSY}$ (2.6, 1.5-5.2), and $B_{current}/\tilde{B}_{MSY}$ (1.6, 1.4-1.9) do not indicate that overfishing of South Pacific albacore is occurring, nor do they indicate that the stock is in an overfished state. However, the distribution of $F_{current}/\tilde{F}_{MSY}$ includes the possibility that overfishing is occurring ($F_{current}/\tilde{F}_{MSY}$ is less than 1 in 5% of scenarios in the structural sensitivity analysis; Figure 53).

Time series of ratios of $F_t/\tilde{F}_{MSY}$, $B_t/\tilde{B}_{MSY}$, and $SB_t/\widetilde{SB}_{MSY}$ (Figure 47 and Figure 48) indicate the fishery's trend towards higher levels of fishing pressure and higher impacts of fishing. F is estimated to remain well below $F_{MSY}$, but the estimated recruitment declines are bringing the estimated biomass closer to $B_{MSY}$.

# 6 Discussion and conclusions

The south Pacific albacore fishery has seen significant changes, with catch rising from 30,000 mt in the mid-1980's, to over 60,000 mt in the mid-2000s, to over 90,000 mt in the last few years. Earlier catch increases were accompanied by declines in CPUE (Bigelow & Hoyle 2012), but the full effects on catch rates of the most recent catch increases have not yet flowed through into the fishery. Albacore CPUE is important for the commercial viability of fishing fleets, and there is concern that the current high catch levels may affect the sustainability of albacore fisheries.

There are a number of ways to measure fishery sustainability, and the WCPFC uses *MSY*-related management parameters by default. However, other management indicators may be more relevant to the commercial sustainability of albacore fisheries. Further discussions on these issues will occur under the management theme of WCPFC-SC8.

In developing the 2012 assessment, we made a number of changes to the structure used in the 2009 and 2011 south Pacific albacore assessments (Hoyle & Davies 2009;Hoyle 2011). 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).

In addition, revised cluster analyses and inclusion of additional data have resulted in more reliable CPUE series than those used in previous assessments (Bigelow & Hoyle 2008;Bigelow & Hoyle

2009; Graham Pilling unpublished data), or the un-standardized data used before 2008. The trends from all regions are relatively consistent with the expected trends, given the different sizes of albacore caught in the various longline fisheries. CPUE in regions when fish are larger tends to decline further and more rapidly than elsewhere. The consistency is not perfect, but suggests that in recent years the CPUE series should be considered a reliable indicator of the biomass trend. The differences from expectation may represent either inconsistency between CPUE and abundance, the effects of spatial variation in growth curves, incomplete mixing between east and west, or a combination of these effects. 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 in general broadly consistent with the changes in catches (Bromhead *et al.* 2009). However, some data are of poor quality, there is some spatial sampling bias, and evidence of spatial and temporal variation (temporal changes in selectivity) that the model does not take into account. For these reasons, the size data were restratified before including it in the model. This restratification reduced the influence of the size data by decreasing the effective sample sizes, and increased its homogeneity through time by increasing the consistency of the sampling locations.

However, despite this intervention, significant 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.

The current stock assessment incorporates recent biological work (Williams *et al.* 2012) indicating that albacore growth curves and maximum sizes vary significantly with longitude across the Pacific, and between the sexes. The growth curve estimated within the assessment is unlikely to represent the average of the population, and even if it was representative, the use of an average growth curve may not be the best way to model the population dynamics of the stock. Moreover, the stock assessment results indicate that *MSY*-related stock status indicators are highly sensitive to the assumed growth curve, particularly estimates of asymptotic length, as are biomass estimates. It is clear that growth variation and uncertainty are significant sources of uncertainty in the model management parameters. This uncertainty could be reduced by using model structures that allow for variation in growth, spatially and between sexes. However, albacore old and large enough to be recruited to longline fisheries are close to fully-grown, so size data contain limited information about total mortality. Alternative sources of such information, such as age data, 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 1975 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 CPUE. The decline is about what would be expected given the increase in fishing pressure, since total catch increases considerably over this period. Further decreases in CPUE may occur in future given the further increases in catch seen recently.

## 6.2 Sensitivity analyses

The sensitivity analyses carried out for this assessment indicate that growth, steepness, and natural mortality are important for all management parameters, and biomass trend-related variables such as effort creep and the choice of CPUE time series are important for biomass-related management parameters. Given the influence of the growth curve, it can be inferred that other issues related to size frequency data will also be influential.

Steepness is unknown and may not be effectively estimable from fisheries data (Conn *et al.* 2010;Lee *et al.* 2012), and so constitutes a relatively intractable source of uncertainty. Alternative values should always be considered in a stock assessment. Over a plausible range of steepness values (0.65 to 0.95), the ratio $F_{current} / F_{MSY}$ varied by a factor of at least 3. The albacore stock assessment is sensitive to assumptions about steepness (Hoyle 2008) because $SB_{MSY} / SB_0$ tends to be low, and the median value ranged from 8% to 34% depending on the steepness.

As discussed above, all model outputs are highly sensitive to the assumed growth curve. Due to time constraints we were only able to explore a relatively limited range of growth curves, but further work in this area is recommended. In particular we recommend exploring modelling approaches that can accommodate spatial and sex-dependent growth variation. We also suggest exploring modelling approaches that are less affected by growth uncertainty. For example, it may be useful to examine spatially-explicit age-based catch curves to ground-truth the model's estimates of total mortality, or potentially to directly include ageing data in the model.

Effort creep, modelled at 0.5% per year, had little effect on $F_{current} / F_{MSY}$, 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 model is also very sensitive to assumptions about the average level of natural mortality though time. Natural mortality effectively scales the productivity of the stock, with higher M estimates implying greater productivity. Natural mortality is unfortunately a very difficult parameter to estimate within stock assessment models, but may be estimable given reliable tag-recapture and size data (Lee *et al.* 2011), and more importantly an appropriate model structure. It may also be useful to carry out a meta-analysis to identify appropriate ranges for uncertainty in this parameter.

The uncertainty grid of models with alternative assumptions was carried out with all combinations of alternative steepness value (0.65, 0.8, and 0.95), ± effort creep, natural mortality of 0.3, 0.4, and 0.5, 5 growth curves selected from 7 alternative options, 3 alternative sets of CPUE time series, and with and without the down-weighting of the early CPUE data. Results showed a very broad range of variation in biomass, fishing mortality, and management parameters, indicating a high degree of structural uncertainty. This may have 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). However, it may be possible to reduce uncertainty by including more realism in the population dynamics modelling.

## 6.3 Management implications

Estimates of fishery impacts on biomass ($1-B_{current}/B_{current,F=0}$) 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 2011 assessment it was 20%. In the current assessment the median estimate is 18%, although the 90% CI ranges from 7% to 48%.

Similarly, the *MSY* estimate has varied through time. From early low estimates of about 35,000 mt (Skillman 1975), estimates using MULTIFAN-CL have varied from 117,000 mt (Hampton 2002) to >200,000 mt (Labelle & Hampton 2003), 183,000 mt (Langley & Hampton 2005), 180,800 mt (Langley & Hampton 2006), 64,000 mt (Hoyle *et al.* 2008a), 81,600 mt (Hoyle & Davies 2009), and 85,100 (Hoyle 2011). The median estimate in this 2012 assessment is 99,100 mt, the mean estimate is 107,900 mt and the 90% CI ranges from 47,000 mt to 215,000 mt. In short, the *MSY* estimate is very uncertain, and very sensitive to the assumptions used in the model.

Current catches (the average of July 2007- June 2010) are estimated to be 79,000 mt, but the catch estimate for the most recent year (July 2010 to June-2011) is 90,000 mt.

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 most 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 Albacore Working Group 2011). Recent spawning stock biomass is estimated to be about 400,000 mt, close to the historical median. Recent fishing mortality rates on the adult component of the stock are high (about 0.75), and recent catches are at about 70,000 mt.

These observations support the hypothesis that, with the current pattern of age-specific selectivity, a fishery continuing at the most recent level – a level that has increased in recent years

– is likely to reduce catch rates and economic returns. Catch increases since 2000 were met by a reduction in CPUE, which together with increasing fuel prices has affected the economics of the albacore fishery.

The 2012 assessment estimates moderate levels of exploitation ($B_{current}/B_{current,F=0}$ = 0.82, and $F_{current}/\tilde{F}_{MSY}$ = 0.21). 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. At the current level of impact the exploitable biomass is estimated to have been depleted by between about 10% and 60%, depending on the fishery, having increased sharply in recent years. The depletion of the spawning potential component of the stock is approximately 47%.

The 2012 stock assessment has made a number of developments from the structure used in the 2009 and 2011 assessments, and identified a significant cause of uncertainty and high priority areas for further work. Future assessments will require improvement to the structure, taking account of new information about spatial and sex differences in growth rates. Managers require advice that is both reliable and useful, and better estimates of population dynamics will in the 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**

- The fishing mortality reference point $F_{current}/F_{MSY}$ has a median estimate of 0.21, (90% CI 0.04-1.08) and on that basis <u>we conclude that there is low risk that overfishing is occurring</u>. The corresponding biomass-based reference points $B_{current}/\tilde{B}_{MSY}$ and $SB_{current}/S\tilde{B}_{MSY}$ are estimated to be above 1.0 (median 1.6, 1.4-1.9, and median 2.6, 1.5-5.2 respectively), and therefore the <u>stock is not in an overfished state</u>.
- The median estimate of *MSY* from the structural sensitivity analysis (99,085 mt, 46-560 – 215,445) is comparable to the recent levels of (estimated) catch from the fishery ($C_{current}$ 78,664 mt, $C_{latest}$ 89,790 mt).
- There is no indication that current levels of catch are causing recruitment overfishing, particularly given the age selectivity of the fisheries.
- Longline catch rates are declining, and catches over the last 10 years have been at historically high levels and are increasing. These trends may be significant for management.
- Management quantities are extremely sensitive to the estimated growth curve. Given that biological research indicates spatial and sex-dependent variation in growth, which is not included in the model, these uncertainties should be understood when considering estimates of management parameters. .

**Recommended model developments**

- Model different growth curves both spatially and by sex within the stock assessment.
- Investigate available spatially explicit and sex-specific data on catch at age from otoliths, in order to ground-truth the model's estimates of total mortality.
- Further 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.
- Investigate alternative reference points to those based on *MSY*, which may be more relevant, precise, and stable across assessments.
- An integrated assessment of North and South Pacific albacore would be beneficial. While separate northern and southern stocks should be maintained as the fundamental stock structure hypothesis, such an integrated assessment may improve the assessment of both stocks because of enhanced overall information on stock dynamics and sharing of common biological characteristics.
- Adjust the spatial definitions of fisheries to take spatial size variation within regions into account.
- Investigate length-based selectivity, which may help to improve the estimated distribution of length-at-age.
- Develop approaches in MULTIFAN-CL to change selectivity seasonally and through time.
- 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 sampling to obtain sex-specific age data, and a representative age distribution of longline catch.
- Biological work to better understand fish movement patterns is desirable. This may include work on otolith microchemistry, and chemical tracers such as fatty acids and stable isotopes.

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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, 0.09, 0.47, 0.75, 0.88, 0.94, 0.97, 0.99, 0.99, 1, 1, 1, 1, 1, 1, 1, 1, 1 | 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 | 0.4 | 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 1/60$^{th}$ actual sample size respectively, with the following exceptions. ESS for Australian, New Caledonian and 'Other' longlines fisheries was assumed to be 1/120$^{th}$ actual; and ESS for Fijian and French Polynesian longline fisheries was assumed to be 1/40$^{th}$ actual. ESS for Troll and Driftnet fisheries is assumed to be 1/10$^{th}$ actual. In each case the maximum actual ESS was 1000 / the ESS divisor.<br>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 at the start of each year. Recruitment is weakly related to spawning potential with a one-year lag via a Beverton-Holt SRR (steepness = 0.8). |
| 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 (Chinese Taipei fisheries), catchability is estimated separately for each season. All non-standardized fisheries have structural time-series variation, with random steps (catchability deviations) taken every twelve months. Catchability deviations are constrained by a prior distribution on the log scale, with a normal 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 standardized fisheries the CPUE SD is applied. For other fisheries the SD is 0.22. |
| Natural mortality | Fixed with mean 0.4. |
| Movement | Not relevant for this model. Fish are assumed to mix fully across all regions. |

Table 4: Scenarios included in the structural sensitivity analysis. Values in the reference case are shown in **bold**.

| Structural features | | Scenarios | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Steepness | | S1<br>0.65 | **S2**<br>**0.8** | S3<br>0.95 | | | | |
| Growth | *Lmax* | **G1**<br>**Estimated** | G2<br>$L_{max\_base}$ + $L_{diff}$ | G3<br>$L_{max\_base}$ + $L_{diff}/2$ | G4<br>$L_{max\_base}$ | G5<br>$L_{max\_base}$ | G6<br>Estimated | G7<br>Estimated |
| | *K* | **Estimated** | $K_{base}$ + $K_{diff}$ | $K_{base}$ + $K_{diff}/2$ | $K_{base}$ + $K_{diff}$ | $K_{base}$ + $K_{diff}$ / 2 | $K_{base}$ + $K_{diff}$ | $K_{base}$ + $K_{diff}$ / 2 |
| Effort creep | | **Cr1**<br>**None** | Cr2<br>0.5% p.a. | | | | | |
| Natural mortality | | M1<br>0.3 | **M2**<br>**0.4** | M3<br>0.5 | | | | |
| CPUE data | | **CPUE1**<br>**All regions** | CPUE2<br>Western regions | CPUE3<br>Eastern regions | | | | |
| Early CPUE | | **EC1**<br>**Down-weighted** | EC2<br>Estimated weights | | | | | |

**Table 5: Details of objective function components.**

| Objective function component | |
|---|---|
| Number of parameters | 5329 |
| | |
| Total catch log-likelihood | 5.2 |
| Length frequency log-likelihood | -138670.6 |
| Tag log-likelihood | 447.8 |
| Effort dev penalty | 103.7 |
| Penalties | 192.5 |
| Total function value | -138018.8 |
| | |
| Maximum gradient at termination | 0.0036 |

**Table 6: Contributions to the log-likelihood by length-frequency data of each fishery, at end of growth estimation phase.**

| Region | Gear | Flag | ssn1 | ssn2 | ssn3 | ssn4 | Total |
|---|---|---|---|---|---|---|---|
| 1 | L | AU | -666.2 | -1024.9 | -410.6 | -800.9 | -2902.7 |
| 1 | L | FJ | -2728.0 | -3468.5 | -3913.4 | -3921.9 | -14031.8 |
| 1 | L | JP | -3783.8 | -2563.0 | -6874.3 | -5385.0 | -18606.2 |
| 1 | L | KR | -2495.6 | -4094.8 | -3430.6 | -2890.2 | -12911.2 |
| 1 | L | NC | -3346.8 | -3646.2 | -3677.8 | -3669.5 | -14340.3 |
| 1 | L | OT | -2620.4 | -3297.2 | -2995.3 | -2196.2 | -11109.1 |
| 1 | L | TW | -6611.9 | -6640.3 | -6336.6 | -7078.8 | -26667.6 |
| 2 | L | AS,WS | -3459.3 | -3794.0 | -3403.5 | -3433.2 | -14090.0 |
| 2 | L | JP | -2446.6 | -3686.5 | -3995.1 | -4818.1 | -14946.3 |
| 2 | L | KR | -3772.1 | -4005.6 | -3730.9 | -3499.8 | -15008.4 |
| 2 | L | OT | -3086.1 | -2944.2 | -3016.6 | -2363.4 | -11410.3 |
| 2 | L | PF | -4214.8 | -3494.0 | -3679.4 | -3989.9 | -15378.1 |
| 2 | L | TO | -3707.3 | -4314.0 | -4330.0 | -4247.5 | -16598.8 |
| 2 | L | TW | -3439.8 | -2043.2 | -3612.6 | -3971.4 | -13066.9 |
| 3 | D | ALL | | | | | -1367.3 |
| 3 | L | AU | -721.4 | -1681.0 | -1996.1 | -1236.2 | -5634.7 |
| 3 | L | JP | -1248.4 | -4266.8 | -5159.6 | -911.9 | -11586.7 |
| 3 | L | KR | -194.4 | -1683.6 | -1579.0 | -435.8 | -3892.8 |
| 3 | L | NZ | -3540.7 | -4325.9 | -3022.0 | -2218.2 | -13106.7 |
| 3 | L | OT | -83.5 | -480.9 | -1724.0 | -568.4 | -2856.8 |
| 3 | L | TW | -323.8 | -3343.3 | -4913.2 | -582.1 | -9162.4 |
| 3 | T | ALL | | | | | -23528.4 |
| 4 | D | ALL | | | | | -686.5 |
| 4 | L | JP | 0 | 0 | 0 | 0 | 0 |
| 4 | L | KR | -281.7 | -2151.0 | -1339.4 | -277.6 | -4049.7 |
| 4 | L | OT | -1035.1 | -1826.0 | -2417.2 | -960.3 | -6238.6 |
| 4 | L | TW | -1238.0 | -5399.4 | -3933.8 | -837.1 | -11408.2 |
| 4 | T | ALL | | | | | -16577.1 |
| 5 | L | JP | -449.7 | -3788.0 | -7344.4 | -2342.8 | -13924.9 |
| 6 | L | JP | -902.3 | -2300.2 | -2971.7 | -2304.0 | -8478.2 |
| Total | | | -56397.4 | -80262.6 | -89807.1 | -64940.3 | -333566.7 |

**Table 7: Descriptions of symbols used in the yield analysis.**

| Symbol | Description |
|---|---|
| $F_{current}$ | Average fishing mortality-at-age for July 2007 to June 2010. |
| $F_{MSY}$ | Fishing mortality-at-age producing the maximum sustainable yield (*MSY*) |
| $\tilde{Y}_{F_{current}}$ | Equilibrium yield at $F_{current}$ |
| $MSY$ | Equilibrium yield at $F_{MSY}$, or maximum sustainable yield |
| $\tilde{B}_0$ | Equilibrium unexploited total biomass |
| $\tilde{B}_{F_{current}}$ | Equilibrium total biomass at $F_{current}$ |
| $\tilde{B}_{MSY}$ | Equilibrium total biomass at *MSY* |
| $S\tilde{B}_0$ | Equilibrium unexploited spawning potential |
| $\tilde{B}_{init}$ | Biomass in 1960 |
| $SB_{F_{current}}$ | Equilibrium spawning potential at $F_{current}$ |
| $S\tilde{B}_{MSY}$ | Equilibrium spawning potential at *MSY* |
| $B_{current}$ | Average current (July 2007 – June 2010) total biomass |
| $SB_{current}$ | Average current (July 2007 – June 2010) spawning potential |
| $SB_{current,F=0}$ | Average current (July 2007 – June 2010) spawning potential in the absence of fishing. |
| $\widetilde{SB}_{init}$ | Spawning potential in 1960 |

**Table 8: Likelihoods, gradients, management parameters and growth parameters from above) the stepwise progression runs from the 2011 assessment to the 2012 reference case, and below) individual runs from the structural sensitivity analysis.**

| Run title | likelihood | gradient | npars | SBcurr/ SBmsy | Fcurr / Fmsy | K | Lmin | Lmax |
|---|---|---|---|---|---|---|---|---|
| 01.2011 assessment | 142164.0 | 8.8E-04 | 6487 | 2.25 | 0.259 | 0.311 | 38.93 | 103.27 |
| 02.2011 assessment rerun | 142164.8 | 1.3E-02 | 6487 | 2.28 | 0.246 | 0.312 | 38.91 | 103.18 |
| 03.New catch and effort | 142128.7 | 9.7E-04 | 6695 | 2.18 | 0.303 | 0.313 | 38.92 | 103.04 |
| 04.New LF data | 169397.8 | 4.2E-02 | 6695 | 2.36 | 0.201 | 0.310 | 38.98 | 102.64 |
| 04b.Remove new TW LF | 153840.2 | 1.8E-03 | 6695 | 2.27 | 0.257 | 0.311 | 38.85 | 103.04 |
| 05.Steepness 0.8 | 169397.7 | 1.3E-02 | 6695 | 2.61 | 0.169 | 0.310 | 38.98 | 102.64 |
| 06. Add CPUE | 170720.1 | 6.8E-03 | 5617 | 2.77 | 0.161 | 0.309 | 39.04 | 102.69 |
| 07.New CPUE approach | 171560.6 | 3.3E-03 | 5329 | 2.75 | 0.163 | 0.307 | 39.08 | 102.76 |
| 08. Change M | 171556.2 | 4.3E-03 | 5329 | 2.78 | 0.168 | 0.307 | 39.13 | 102.51 |
| 09. Change sex ratio | 171556.2 | 6.9E-04 | 5329 | 2.83 | 0.192 | 0.308 | 39.13 | 102.50 |
| 10. New spawning ptntl | 171556.2 | 3.2E-04 | 5329 | 2.68 | 0.129 | 0.308 | 39.13 | 102.50 |
| 11. Size restratifica | 138021.9 | 1.2E-03 | 5329 | 2.67 | 0.146 | 0.312 | 38.95 | 102.41 |
| 12. Lognormal bias adj | 138018.8 | 3.6E-03 | 5329 | 2.58 | 0.143 | 0.312 | 38.95 | 102.39 |
| 13. Reference case | 138018.8 | 3.6E-03 | 5329 | 2.58 | 0.143 | 0.312 | 38.95 | 102.39 |
| S01. 2regions w mvmt | 138021.7 | 4.5E-04 | 5337 | 2.41 | 0.186 | 0.312 | 38.86 | 102.69 |
| S02. 2regions w/o mvmt | 138021.7 | 6.6E-04 | 5329 | 2.41 | 0.186 | 0.312 | 38.86 | 102.69 |
| S03a. R1_CPUE | 138167.9 | 1.3E-04 | 5329 | 3.17 | 0.126 | 0.310 | 39.13 | 102.42 |
| S03b. R2_CPUE | 138148.0 | 2.9E-03 | 5329 | 2.71 | 0.141 | 0.309 | 39.06 | 102.54 |
| S03c. R3_CPUE | 138174.3 | 9.6E-03 | 5329 | 3.20 | 0.118 | 0.312 | 39.00 | 102.33 |
| S03d. R4_CPUE | 138117.1 | 1.1E-02 | 5329 | 2.64 | 0.151 | 0.308 | 39.14 | 102.66 |
| S04a. East strata | 63495.8 | 7.2E-05 | 2756 | 2.02 | 0.205 | 0.320 | 34.59 | 104.50 |
| S04a. West strata | 74553.4 | 1.5E-04 | 2653 | 3.16 | 0.087 | 0.301 | 40.12 | 100.90 |
| S05.asymp_sel_PF | 138018.7 | 6.3E-05 | 5329 | 2.59 | 0.143 | 0.312 | 38.95 | 102.39 |
| S06.asymp_sel_R2 | 138017.2 | 9.4E-05 | 5329 | 2.63 | 0.130 | 0.317 | 38.92 | 101.78 |
| | | | | | | | | |
| Steepness 0.65 | 138087.6 | 1.78E-04 | 5329 | 2.05 | 0.253 | 0.310 | 39.12 | 102.47 |
| Steepness 0.95 | 138087.1 | 3.31E-04 | 5329 | 3.95 | 0.068 | 0.310 | 39.12 | 102.46 |
| Alt growth 1 | 138060 | 1.88E-03 | 5329 | 1.91 | 0.691 | 0.386 | 38.88 | 104.05 |
| Alt growth 2 | 138077.7 | 4.77E-04 | 5329 | 2.40 | 0.351 | 0.350 | 38.88 | 103.31 |
| Alt growth 3 | 138066.2 | 8.22E-05 | 5329 | 2.29 | 0.424 | 0.386 | 38.95 | 102.39 |
| Alt growth 4 | 138083.6 | 5.54E-05 | 5329 | 2.50 | 0.260 | 0.349 | 38.95 | 102.39 |
| Alt growth 5 | 138062.5 | 1.08E-05 | 5329 | 2.75 | 0.100 | 0.386 | 38.95 | 98.36 |
| Alt growth 6 | 138075.6 | 2.16E-04 | 5329 | 2.69 | 0.102 | 0.349 | 38.95 | 99.63 |
| Effort creep 0.5% | 138085.4 | 1.39E-03 | 5329 | 2.42 | 0.149 | 0.310 | 39.11 | 102.41 |
| M=0.3 | 138082.1 | 1.24E-03 | 5329 | 2.29 | 0.225 | 0.310 | 39.40 | 101.47 |
| M=0.5 | 138087.9 | 4.17E-03 | 5329 | 2.97 | 0.078 | 0.307 | 38.90 | 103.40 |
| CPUE west | 138167.9 | 3.59E-03 | 5329 | 3.17 | 0.126 | 0.310 | 39.13 | 102.42 |
| CPUE east | 138092.6 | 1.03E-02 | 5329 | 2.56 | 0.143 | 0.310 | 39.11 | 102.46 |
| early CPUE full wt | 138086.1 | 8.25E-05 | 5329 | 2.57 | 0.143 | 0.310 | 39.11 | 102.43 |

**Table 9: Management parameters estimated from the 2012 grid and reference case model, and estimates from the 2011 assessment, for comparison.**

| | Grid Median | Grid Mean | 2012 Ref case | 2011 base case |
|---|---|---|---|---|
| $C_{current}$ | 78,664 | 78,355 | 77,439 | 54,520 |
| $C_{latest}$ | 89,790 | 89,372 | 88,528 | 56,275 |
| $Y_{F_{current}}$ | 66,255 | 65,787 | 77,820 | 57,120 |
| $Y_{F_{MSY}}$ or $MSY$ | 99,085 | 107,895 | 133,200 | 85,130 |
| $Y_{F_{current}}/MSY$ | 0.7 | 0.71 | 0.58 | 0.67 |
| $C_{current}/MSY$ | 0.79 | 0.92 | 0.58 | 0.64 |
| $C_{latest}/MSY$ | 0.9 | 1.05 | 0.66 | 0.66 |
| $F_{MSY}$ | 0.16 | 0.17 | 0.16 | 0.1 |
| $F_{mult}$ | 4.81 | 7.59 | 6.98 | 3.86 |
| $F_{current}/F_{MSY}$ | 0.21 | 0.33 | 0.14 | 0.26 |
| $B_0$ | 1,131,000 | 1,308,595 | 1,629,000 | 1,140,000 |
| $B_{MSY}$ | 587,000 | 663,906 | 835,200 | 605,400 |
| $B_{MSY}/B_0$ | 0.51 | 0.5 | 0.51 | 0.530 |
| $B_{current}$ | 1,028,983 | 1,058,825 | 1,263,700 | 761,570 |
| $B_{latest}$ | 1,013,550 | 1,049,267 | 1,298,400 | 816,560 |
| $B_{init}$ | 1,721,250 | 2,079,737 | 2,859,900 | 1,759,000 |
| $B_{F_{current}}$ | 909,300 | 1,017,640 | 1,327,000 | 902,700 |
| $B_{current_{F=0}}$ | 1,192,050 | 1,270,139 | 1,462,700 | 950,273 |
| $B_{latest_{F=0}}$ | 1,220,600 | 1,296,339 | 1,532,100 | 988,750 |
| $SB_0$ | 442,350 | 556,072 | 721,400 | 400,400 |
| $SB_{MSY}$ | 108,100 | 125,699 | 168,900 | 104,100 |
| $SB_{MSY}/SB_0$ | 0.23 | 0.22 | 0.23 | 0.26 |
| $SB_{current}$ | 253,117 | 334,142 | 436,587 | 234,367 |
| $SB_{latest}$ | 241,700 | 321,250 | 431,820 | 189,210 |
| $SB_{init}$ | 621,915 | 830,656 | 1,229,500 | 591,980 |
| $SB_{F_{current}}$ | 229,650 | 324,625 | 468,500 | 251,200 |
| $SB_{current_{F=0}}$ | 448,288 | 524,167 | 617,947 | 371,877 |
| $SB_{latest_{F=0}}$ | 462,685 | 542,487 | 644,290 | 313,970 |
| $B_{current}/B_0$ | 0.81 | 0.81 | 0.78 | 0.67 |
| $B_{latest}/B_0$ | 0.8 | 0.79 | 0.80 | 0.72 |
| $B_{F_{current}}/B_0$ | 0.76 | 0.73 | 0.81 | 0.79 |
| $B_{current}/B_{MSY}$ | 1.62 | 1.61 | 1.51 | 1.26 |
| $B_{latest}/B_{MSY}$ | 1.57 | 1.56 | 1.55 | 1.35 |
| $B_{F_{current}}/B_{MSY}$ | 1.49 | 1.45 | 1.59 | 1.49 |
| $B_{current}/B_{current_{F=0}}$ | 0.82 | 0.8 | 0.86 | 0.8 |
| $B_{latest}/B_{latest_{F=0}}$ | 0.8 | 0.77 | 0.85 | 0.83 |
| $B_{current}/B_{init}$ | 0.57 | 0.61 | 0.44 | 0.43 |
| $SB_{current}/SB_0$ | 0.59 | 0.59 | 0.61 | 0.59 |
| $SB_{latest}/SB_0$ | 0.56 | 0.56 | 0.60 | 0.47 |
| $SB_{F_{current}}/SB_0$ | 0.56 | 0.53 | 0.65 | 0.63 |
| $SB_{current}/SB_{MSY}$ | 2.56 | 2.88 | 2.58 | 2.25 |
| $SB_{latest}/SB_{MSY}$ | 2.38 | 2.74 | 2.56 | 1.82 |
| $SB_{F_{current}}/SB_{MSY}$ | 2.39 | 2.64 | 2.77 | 2.41 |
| $SB_{curr}/SB_{curr_{F=0}}$ | 0.63 | 0.6 | 0.71 | 0.63 |
| $SB_{latest}/SB_{latest_{F=0}}$ | 0.58 | 0.56 | 0.67 | 0.6 |
| $SB_{current}/SB_{init}$ | 0.44 | 0.47 | 0.36 | 0.40 |

**Table 10: Estimates and 90% distributions of management quantities from the uncertainty analysis. The highlighted rows are ratios of comparable quantities at the same point in time (black shading) and ratios of comparable equilibrium quantities (grey shading).**

| | Median | Mean | SD | 5% | 95% |
|---|---|---|---|---|---|
| $C_{current}$ | 78,664 | 78,355 | 3,581 | 76,231 | 80,508 |
| $C_{latest}$ | 89,790 | 89,372 | 4,076 | 87,019 | 91,305 |
| $Y_{F_{current}}$ | 66,255 | 65,787 | 12,737 | 46,330 | 85,524 |
| $Y_{F_{MSY}}$ or $MSY$ | 99,085 | 107,895 | 54,425 | 46,560 | 215,445 |
| $Y_{F_{current}}/MSY$ | 0.7 | 0.71 | 0.204 | 0.371 | 0.99 |
| $C_{current}/MSY$ | 0.79 | 0.92 | 0.44 | 0.356 | 1.71 |
| $C_{latest}/MSY$ | 0.9 | 1.05 | 0.501 | 0.406 | 1.94 |
| $F_{MSY}$ | 0.16 | 0.17 | 0.034 | 0.122 | 0.21 |
| $F_{mult}$ | 4.81 | 7.59 | 8.116 | 0.923 | 22.72 |
| $F_{current}/F_{MSY}$ | 0.21 | 0.33 | 0.348 | 0.044 | 1.08 |
| $B_0$ | 1,131,000 | 1,308,595 | 596,766 | 612,895 | 2,447,300 |
| $B_{MSY}$ | 587,000 | 663,906 | 318,260 | 286,495 | 1,299,350 |
| $B_{MSY}/B_0$ | 0.51 | 0.5 | 0.035 | 0.443 | 0.55 |
| $B_{current}$ | 1,028,983 | 1,058,825 | 486,181 | 455,477 | 2,047,317 |
| $B_{latest}$ | 1,013,550 | 1,049,267 | 526,749 | 407,296 | 2,161,525 |
| $B_{init}$ | 1,721,250 | 2,079,737 | 1,341,860 | 463,143 | 4,546,415 |
| $B_{F_{current}}$ | 909,300 | 1,017,640 | 597,130 | 302,195 | 2,217,050 |
| $B_{current_{F=0}}$ | 1,192,050 | 1,270,139 | 457,694 | 738,821 | 2,197,948 |
| $B_{latest_{F=0}}$ | 1,220,600 | 1,296,339 | 497,158 | 728,757 | 2,346,310 |
| $SB_0$ | 442,350 | 556,072 | 236,857 | 294,545 | 927,510 |
| $SB_{MSY}$ | 108,100 | 125,699 | 66,270 | 45,739 | 260,625 |
| $SB_{MSY}/SB_0$ | 0.23 | 0.22 | 0.059 | 0.124 | 0.3 |
| $SB_{current}$ | 253,117 | 334,142 | 170,379 | 134,856 | 652,037 |
| $SB_{latest}$ | 241,700 | 321,250 | 170,508 | 127,259 | 621,281 |
| $SB_{init}$ | 621,915 | 830,656 | 535,427 | 209,627 | 1,724,545 |
| $SB_{F_{current}}$ | 229,650 | 324,625 | 209,427 | 86,754 | 656,605 |
| $SB_{current_{F=0}}$ | 448,288 | 524,167 | 168,395 | 332,731 | 788,177 |
| $SB_{latest_{F=0}}$ | 462,685 | 542,487 | 167,517 | 354,530 | 794,402 |
| $B_{current}/B_0$ | 0.81 | 0.81 | 0.089 | 0.66 | 0.96 |
| $B_{latest}/B_0$ | 0.8 | 0.79 | 0.09 | 0.622 | 0.91 |
| $B_{F_{current}}/B_0$ | 0.76 | 0.73 | 0.136 | 0.468 | 0.9 |
| $B_{current}/B_{MSY}$ | 1.62 | 1.61 | 0.149 | 1.369 | 1.88 |
| $B_{latest}/B_{MSY}$ | 1.57 | 1.56 | 0.14 | 1.284 | 1.78 |
| $B_{F_{current}}/B_{MSY}$ | 1.49 | 1.45 | 0.254 | 0.964 | 1.81 |
| $B_{current}/B_{current_{F=0}}$ | 0.82 | 0.8 | 0.099 | 0.617 | 0.93 |
| $B_{latest}/B_{latest_{F=0}}$ | 0.8 | 0.77 | 0.115 | 0.559 | 0.92 |
| $B_{current}/B_{init}$ | 0.57 | 0.61 | 0.205 | 0.374 | 1.01 |
| $SB_{current}/SB_0$ | 0.59 | 0.59 | 0.104 | 0.407 | 0.76 |
| $SB_{latest}/SB_0$ | 0.56 | 0.56 | 0.106 | 0.37 | 0.72 |
| $SB_{F_{current}}/SB_0$ | 0.56 | 0.53 | 0.162 | 0.256 | 0.76 |
| $SB_{current}/SB_{MSY}$ | 2.56 | 2.88 | 1.175 | 1.457 | 5.2 |
| $SB_{latest}/SB_{MSY}$ | 2.38 | 2.74 | 1.155 | 1.327 | 5.18 |
| $SB_{F_{current}}/SB_{MSY}$ | 2.39 | 2.64 | 1.324 | 0.943 | 5.27 |
| $SB_{curr}/SB_{curr_{F=0}}$ | 0.63 | 0.6 | 0.142 | 0.347 | 0.8 |
| $SB_{latest}/SB_{latest_{F=0}}$ | 0.58 | 0.56 | 0.15 | 0.307 | 0.77 |
| $SB_{current}/SB_{init}$ | 0.44 | 0.47 | 0.142 | 0.301 | 0.75 |

**Table 11a: Median estimates of management quantities from the uncertainty analysis, for each dimension in the analysis. The highlighted rows are ratios of comparable quantities at the same point in time (black shading) and ratios of comparable equilibrium quantities (grey shading). For scenario definitions see Table 4.**

| | G1 | G2 | G3 | G4 | G5 | G6 | G7 |
|---|---|---|---|---|---|---|---|
| $C_{current}$ | 77,657 | 79,254 | 78,940 | 79,285 | 78,454 | 77,030 | 76,469 |
| $C_{latest}$ | 88,392 | 91,651 | 89,854 | 90,932 | 89,343 | 87,951 | 87,391 |
| $Y_{F_{current}}$ | 79,035 | 48,920 | 56,390 | 52,650 | 62,025 | 77,175 | 79,915 |
| $Y_{F_{MSY}}$ *or* $MSY$ | 138,150 | 50,285 | 65,970 | 59,705 | 83,540 | 145,100 | 165,200 |
| $Y_{F_{current}}/MSY$ | 0.58 | 0.98 | 0.86 | 0.91 | 0.78 | 0.5 | 0.48 |
| $C_{current}/MSY$ | 0.56 | 1.59 | 1.21 | 1.35 | 0.95 | 0.53 | 0.47 |
| $C_{latest}/MSY$ | 0.65 | 1.82 | 1.38 | 1.53 | 1.08 | 0.61 | 0.54 |
| $F_{MSY}$ | 0.16 | 0.17 | 0.16 | 0.16 | 0.16 | 0.16 | 0.16 |
| $F_{mult}$ | 7.7 | 1.45 | 2.82 | 2.33 | 3.8 | 9.67 | 9.79 |
| $F_{current}/F_{MSY}$ | 0.13 | 0.69 | 0.35 | 0.43 | 0.26 | 0.1 | 0.1 |
| $B_0$ | 1,690,500 | 647,600 | 804,950 | 706,600 | 1,026,000 | 1,940,000 | 2,050,000 |
| $B_{MSY}$ | 849,500 | 340,500 | 401,050 | 367,250 | 510,550 | 944,400 | 1,042,500 |
| $B_{MSY}/B_0$ | 0.51 | 0.52 | 0.52 | 0.52 | 0.51 | 0.5 | 0.5 |
| $B_{current}$ | 1,274,033 | 506,487 | 693,937 | 627,948 | 836,140 | 1,534,967 | 1,581,317 |
| $B_{latest}$ | 1,320,450 | 455,900 | 663,640 | 585,045 | 825,805 | 1,546,550 | 1,650,100 |
| $B_{init}$ | 2,986,200 | 517,975 | 1,015,800 | 827,140 | 1,506,550 | 3,484,500 | 3,789,350 |
| $B_{F_{current}}$ | 1,348,000 | 340,000 | 535,150 | 443,150 | 735,650 | 1,645,000 | 1,758,000 |
| $B_{current_{F=0}}$ | 1,473,267 | 720,367 | 900,762 | 834,852 | 1,039,167 | 1,724,717 | 1,772,650 |
| $B_{latest_{F=0}}$ | 1,554,100 | 705,625 | 905,860 | 827,395 | 1,063,950 | 1,769,300 | 1,875,050 |
| $SB_0$ | 740,500 | 253,600 | 367,000 | 312,750 | 439,800 | 808,750 | 881,050 |
| $SB_{MSY}$ | 172,150 | 56,920 | 83,190 | 69,815 | 103,700 | 188,650 | 204,950 |
| $SB_{MSY}/SB_0$ | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 |
| $SB_{current}$ | 486,800 | 109,569 | 194,768 | 159,068 | 252,382 | 508,317 | 538,715 |
| $SB_{latest}$ | 471,150 | 107,720 | 185,360 | 152,895 | 239,990 | 509,200 | 548,495 |
| $SB_{init}$ | 1,259,550 | 178,965 | 386,175 | 303,935 | 583,285 | 1,423,600 | 1,584,300 |
| $SB_{F_{current}}$ | 512,850 | 72,690 | 148,750 | 110,500 | 221,950 | 547,700 | 632,300 |
| $SB_{current_{F=0}}$ | 677,695 | 293,207 | 380,695 | 339,912 | 448,288 | 691,638 | 726,132 |
| $SB_{latest_{F=0}}$ | 681,595 | 318,750 | 403,270 | 362,600 | 462,685 | 713,780 | 752,240 |
| $B_{current}/B_0$ | 0.78 | 0.87 | 0.85 | 0.88 | 0.82 | 0.8 | 0.78 |
| $B_{latest}/B_0$ | 0.8 | 0.77 | 0.8 | 0.8 | 0.79 | 0.81 | 0.81 |
| $B_{F_{current}}/B_0$ | 0.81 | 0.58 | 0.69 | 0.66 | 0.73 | 0.85 | 0.85 |
| $B_{current}/B_{MSY}$ | 1.53 | 1.68 | 1.66 | 1.7 | 1.62 | 1.61 | 1.55 |
| $B_{latest}/B_{MSY}$ | 1.58 | 1.48 | 1.55 | 1.55 | 1.55 | 1.62 | 1.6 |
| $B_{F_{current}}/B_{MSY}$ | 1.6 | 1.12 | 1.33 | 1.26 | 1.42 | 1.66 | 1.66 |
| $B_{current}/B_{current_{F=0}}$ | 0.86 | 0.7 | 0.77 | 0.75 | 0.8 | 0.89 | 0.89 |
| $B_{latest}/B_{latest_{F=0}}$ | 0.85 | 0.65 | 0.73 | 0.71 | 0.78 | 0.87 | 0.88 |
| $B_{current}/B_{init}$ | 0.46 | 1.01 | 0.7 | 0.79 | 0.58 | 0.44 | 0.42 |
| $SB_{current}/SB_0$ | 0.61 | 0.44 | 0.56 | 0.53 | 0.58 | 0.64 | 0.62 |
| $SB_{latest}/SB_0$ | 0.6 | 0.43 | 0.52 | 0.5 | 0.55 | 0.64 | 0.63 |
| $SB_{F_{current}}/SB_0$ | 0.66 | 0.29 | 0.44 | 0.39 | 0.51 | 0.71 | 0.72 |
| $SB_{current}/SB_{MSY}$ | 2.73 | 1.95 | 2.49 | 2.35 | 2.62 | 2.93 | 2.87 |
| $SB_{latest}/SB_{MSY}$ | 2.6 | 1.88 | 2.27 | 2.17 | 2.4 | 2.74 | 2.78 |
| $SB_{F_{current}}/SB_{MSY}$ | 2.76 | 1.27 | 1.89 | 1.68 | 2.18 | 3.03 | 3.05 |
| $SB_{curr}/SB_{curr_{F=0}}$ | 0.7 | 0.37 | 0.52 | 0.47 | 0.58 | 0.75 | 0.76 |
| $SB_{latest}/SB_{latest_{F=0}}$ | 0.67 | 0.34 | 0.47 | 0.42 | 0.53 | 0.72 | 0.73 |
| $SB_{current}/SB_{init}$ | 0.37 | 0.62 | 0.49 | 0.52 | 0.43 | 0.36 | 0.35 |

**Table 11b: Median estimates of management quantities from the uncertainty analysis, for each dimension in the analysis. The highlighted rows are ratios of comparable quantities at the same point in time (black shading) and ratios of comparable equilibrium quantities (grey shading). For scenario definitions see Table 4.**

| | S1 | S2 | S3 | Cr1 | Cr2 | EC1 | EC2 |
|---|---|---|---|---|---|---|---|
| $C_{current}$ | 78,714 | 78,657 | 78,622 | 78,743 | 78,612 | 78,638 | 78,674 |
| $C_{latest}$ | 89,924 | 89,852 | 89,809 | 89,988 | 89,695 | 89,847 | 89,865 |
| $Y_{F_{current}}$ | 63,380 | 65,905 | 67,330 | 64,290 | 67,045 | 65,770 | 66,460 |
| $Y_{F_{MSY}}$ or $MSY$ | 78,610 | 97,040 | 117,700 | 96,115 | 99,330 | 96,115 | 97,855 |
| $Y_{F_{current}}/MSY$ | 0.79 | 0.68 | 0.58 | 0.72 | 0.72 | 0.73 | 0.71 |
| $C_{current}/MSY$ | 1 | 0.81 | 0.67 | 0.81 | 0.77 | 0.81 | 0.79 |
| $C_{latest}/MSY$ | 1.14 | 0.92 | 0.77 | 0.93 | 0.88 | 0.93 | 0.91 |
| $F_{MSY}$ | 0.13 | 0.16 | 0.21 | 0.16 | 0.16 | 0.16 | 0.16 |
| $F_{mult}$ | 2.76 | 4.77 | 8.99 | 4.9 | 4.76 | 4.76 | 4.83 |
| $F_{current}/F_{MSY}$ | 0.36 | 0.21 | 0.11 | 0.2 | 0.21 | 0.21 | 0.21 |
| $B_0$ | 1,159,000 | 1,131,000 | 1,114,000 | 1,118,500 | 1,178,500 | 1,126,000 | 1,135,500 |
| $B_{MSY}$ | 638,300 | 620,200 | 574,350 | 576,650 | 604,250 | 577,050 | 595,200 |
| $B_{MSY}/B_0$ | 0.52 | 0.52 | 0.49 | 0.51 | 0.51 | 0.51 | 0.51 |
| $B_{current}$ | 1,026,083 | 1,028,983 | 1,032,633 | 1,036,367 | 1,027,567 | 1,026,583 | 1,035,200 |
| $B_{latest}$ | 997,030 | 1,011,175 | 1,020,250 | 1,013,550 | 1,007,975 | 991,920 | 1,026,700 |
| $B_{init}$ | 1,755,550 | 1,714,500 | 1,695,600 | 1,668,450 | 1,845,200 | 1,671,250 | 1,770,900 |
| $B_{F_{current}}$ | 875,500 | 911,700 | 931,900 | 879,850 | 930,300 | 907,150 | 916,050 |
| $B_{current_{F=0}}$ | 1,189,717 | 1,191,833 | 1,193,550 | 1,198,533 | 1,189,900 | 1,189,900 | 1,196,133 |
| $B_{latest_{F=0}}$ | 1,213,750 | 1,221,950 | 1,227,750 | 1,220,250 | 1,221,450 | 1,214,950 | 1,225,400 |
| $SB_0$ | 453,900 | 435,700 | 428,950 | 436,550 | 452,650 | 437,100 | 446,950 |
| $SB_{MSY}$ | 134,000 | 103,700 | 65,875 | 106,650 | 110,450 | 107,950 | 109,100 |
| $SB_{MSY}/SB_0$ | 0.29 | 0.23 | 0.15 | 0.23 | 0.23 | 0.23 | 0.23 |
| $SB_{current}$ | 254,388 | 251,910 | 253,382 | 253,875 | 251,483 | 251,710 | 255,118 |
| $SB_{latest}$ | 242,260 | 241,280 | 242,270 | 244,225 | 238,810 | 240,330 | 243,305 |
| $SB_{init}$ | 631,480 | 615,445 | 612,165 | 566,200 | 659,660 | 592,325 | 645,120 |
| $SB_{F_{current}}$ | 217,900 | 228,850 | 236,750 | 221,950 | 232,350 | 227,600 | 231,350 |
| $SB_{current_{F=0}}$ | 447,185 | 447,893 | 449,090 | 449,838 | 448,095 | 446,620 | 449,992 |
| $SB_{latest_{F=0}}$ | 461,890 | 462,620 | 464,040 | 464,950 | 462,685 | 458,420 | 465,910 |
| $B_{current}/B_0$ | 0.79 | 0.82 | 0.83 | 0.83 | 0.79 | 0.81 | 0.81 |
| $B_{latest}/B_0$ | 0.77 | 0.8 | 0.83 | 0.82 | 0.78 | 0.8 | 0.8 |
| $B_{F_{current}}/B_0$ | 0.72 | 0.76 | 0.78 | 0.76 | 0.76 | 0.76 | 0.76 |
| $B_{current}/B_{MSY}$ | 1.5 | 1.59 | 1.74 | 1.67 | 1.59 | 1.62 | 1.62 |
| $B_{latest}/B_{MSY}$ | 1.48 | 1.56 | 1.7 | 1.6 | 1.53 | 1.57 | 1.57 |
| $B_{F_{current}}/B_{MSY}$ | 1.36 | 1.46 | 1.61 | 1.49 | 1.49 | 1.49 | 1.49 |
| $B_{current}/B_{current_{F=0}}$ | 0.82 | 0.82 | 0.82 | 0.82 | 0.81 | 0.81 | 0.82 |
| $B_{latest}/B_{latest_{F=0}}$ | 0.79 | 0.79 | 0.8 | 0.8 | 0.79 | 0.79 | 0.8 |
| $B_{current}/B_{init}$ | 0.56 | 0.57 | 0.58 | 0.6 | 0.54 | 0.59 | 0.54 |
| $SB_{current}/SB_0$ | 0.57 | 0.59 | 0.6 | 0.6 | 0.57 | 0.59 | 0.58 |
| $SB_{latest}/SB_0$ | 0.55 | 0.56 | 0.57 | 0.58 | 0.54 | 0.56 | 0.56 |
| $SB_{F_{current}}/SB_0$ | 0.53 | 0.56 | 0.59 | 0.56 | 0.56 | 0.55 | 0.57 |
| $SB_{current}/SB_{MSY}$ | 1.95 | 2.55 | 3.95 | 2.61 | 2.48 | 2.55 | 2.54 |
| $SB_{latest}/SB_{MSY}$ | 1.87 | 2.45 | 3.72 | 2.43 | 2.28 | 2.38 | 2.38 |
| $SB_{F_{current}}/SB_{MSY}$ | 1.86 | 2.43 | 3.59 | 2.35 | 2.33 | 2.35 | 2.35 |
| $SB_{curr}/SB_{curr_{F=0}}$ | 0.63 | 0.63 | 0.63 | 0.63 | 0.63 | 0.63 | 0.63 |
| $SB_{latest}/SB_{latest_{F=0}}$ | 0.58 | 0.58 | 0.58 | 0.59 | 0.58 | 0.58 | 0.58 |
| $SB_{current}/SB_{init}$ | 0.45 | 0.45 | 0.46 | 0.48 | 0.42 | 0.47 | 0.44 |

**Table 11c: Median estimates of management quantities from the uncertainty analysis, for each dimension in the analysis. The highlighted rows are ratios of comparable quantities at the same point in time (black shading) and ratios of comparable equilibrium quantities (grey shading). For scenario definitions see Table 4.**

| | M1 | M2 | M3 | Cpue1 | Cpue2 | Cpue3 |
|---|---|---|---|---|---|---|
| $C_{current}$ | 78,784 | 78,592 | 78,664 | 78,344 | 79,728 | 78,365 |
| $C_{latest}$ | 89,918 | 89,842 | 89,830 | 89,200 | 90,639 | 89,151 |
| $Y_{F_{current}}$ | 55,410 | 64,740 | 69,475 | 69,630 | 58,345 | 69,640 |
| $Y_{F_{MSY}}$ or $MSY$ | 59,770 | 85,140 | 130,600 | 100,400 | 85,465 | 102,450 |
| $Y_{F_{current}}/MSY$ | 0.86 | 0.75 | 0.56 | 0.74 | 0.7 | 0.74 |
| $C_{current}/MSY$ | 1.31 | 0.92 | 0.6 | 0.77 | 0.93 | 0.76 |
| $C_{latest}/MSY$ | 1.49 | 1.05 | 0.69 | 0.88 | 1.06 | 0.87 |
| $F_{MSY}$ | 0.16 | 0.16 | 0.16 | 0.16 | 0.16 | 0.16 |
| $F_{mult}$ | 2.61 | 5.19 | 9.37 | 4.77 | 4.77 | 4.84 |
| $F_{current}/F_{MSY}$ | 0.38 | 0.19 | 0.11 | 0.21 | 0.21 | 0.21 |
| $B_0$ | 761,750 | 1,026,000 | 1,521,000 | 1,165,000 | 946,700 | 1,165,000 |
| $B_{MSY}$ | 361,400 | 510,550 | 799,500 | 641,300 | 517,650 | 631,550 |
| $B_{MSY}/B_0$ | 0.47 | 0.52 | 0.55 | 0.51 | 0.51 | 0.51 |
| $B_{current}$ | 557,215 | 836,140 | 1,275,133 | 1,040,350 | 918,447 | 1,033,667 |
| $B_{latest}$ | 525,500 | 825,805 | 1,308,200 | 1,033,300 | 838,930 | 1,030,950 |
| $B_{init}$ | 832,195 | 1,506,550 | 2,573,350 | 1,814,100 | 1,249,150 | 1,867,500 |
| $B_{F_{current}}$ | 398,950 | 735,650 | 1,263,000 | 932,600 | 747,800 | 924,400 |
| $B_{current_{F=0}}$ | 834,927 | 1,039,167 | 1,433,233 | 1,201,317 | 1,080,050 | 1,194,617 |
| $B_{latest_{F=0}}$ | 841,465 | 1,063,950 | 1,499,550 | 1,227,750 | 1,035,500 | 1,225,450 |
| $SB_0$ | 422,750 | 445,650 | 508,200 | 453,900 | 397,650 | 463,000 |
| $SB_{MSY}$ | 122,500 | 107,300 | 92,365 | 109,350 | 94,960 | 110,750 |
| $SB_{MSY}/SB_0$ | 0.25 | 0.23 | 0.22 | 0.23 | 0.23 | 0.23 |
| $SB_{current}$ | 197,348 | 252,382 | 317,948 | 253,117 | 242,738 | 257,487 |
| $SB_{latest}$ | 181,345 | 239,990 | 308,165 | 243,220 | 211,105 | 245,065 |
| $SB_{init}$ | 419,985 | 616,330 | 825,400 | 662,900 | 430,080 | 667,970 |
| $SB_{F_{current}}$ | 138,150 | 221,950 | 318,850 | 230,450 | 184,200 | 235,050 |
| $SB_{current_{F=0}}$ | 449,822 | 434,105 | 457,020 | 449,822 | 442,307 | 451,682 |
| $SB_{latest_{F=0}}$ | 467,220 | 451,355 | 475,295 | 468,435 | 446,100 | 470,790 |
| $B_{current}/B_0$ | 0.72 | 0.84 | 0.89 | 0.79 | 0.87 | 0.78 |
| $B_{latest}/B_0$ | 0.68 | 0.8 | 0.88 | 0.79 | 0.81 | 0.79 |
| $B_{F_{current}}/B_0$ | 0.59 | 0.73 | 0.84 | 0.76 | 0.76 | 0.76 |
| $B_{current}/B_{MSY}$ | 1.56 | 1.63 | 1.65 | 1.57 | 1.71 | 1.55 |
| $B_{latest}/B_{MSY}$ | 1.49 | 1.58 | 1.61 | 1.56 | 1.59 | 1.54 |
| $B_{F_{current}}/B_{MSY}$ | 1.32 | 1.49 | 1.57 | 1.49 | 1.47 | 1.49 |
| $B_{current}/B_{current_{F=0}}$ | 0.67 | 0.8 | 0.89 | 0.81 | 0.83 | 0.81 |
| $B_{latest}/B_{latest_{F=0}}$ | 0.62 | 0.78 | 0.87 | 0.8 | 0.79 | 0.8 |
| $B_{current}/B_{init}$ | 0.66 | 0.58 | 0.54 | 0.53 | 0.68 | 0.52 |
| $SB_{current}/SB_0$ | 0.48 | 0.58 | 0.64 | 0.56 | 0.68 | 0.56 |
| $SB_{latest}/SB_0$ | 0.43 | 0.55 | 0.63 | 0.55 | 0.62 | 0.55 |
| $SB_{F_{current}}/SB_0$ | 0.35 | 0.51 | 0.64 | 0.57 | 0.55 | 0.56 |
| $SB_{current}/SB_{MSY}$ | 2.09 | 2.52 | 2.95 | 2.38 | 2.78 | 2.37 |
| $SB_{latest}/SB_{MSY}$ | 1.93 | 2.39 | 2.93 | 2.31 | 2.52 | 2.29 |
| $SB_{F_{current}}/SB_{MSY}$ | 1.86 | 2.33 | 2.95 | 2.35 | 2.37 | 2.34 |
| $SB_{curr}/SB_{curr_{F=0}}$ | 0.44 | 0.58 | 0.7 | 0.63 | 0.62 | 0.63 |
| $SB_{latest}/SB_{latest_{F=0}}$ | 0.39 | 0.53 | 0.65 | 0.59 | 0.55 | 0.58 |
| $SB_{current}/SB_{init}$ | 0.49 | 0.45 | 0.43 | 0.4 | 0.56 | 0.39 |

# 10 Figures

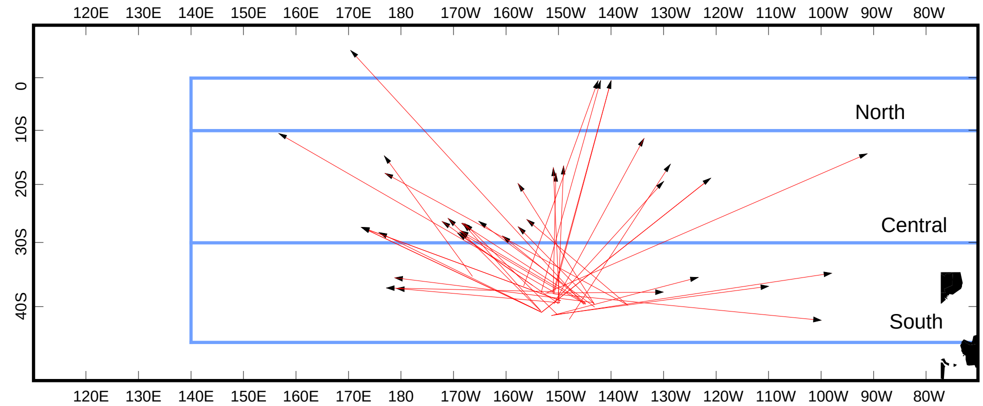


**Figure 1: Movements of tagged South Pacific albacore (from Labelle and Hampton 2003).**

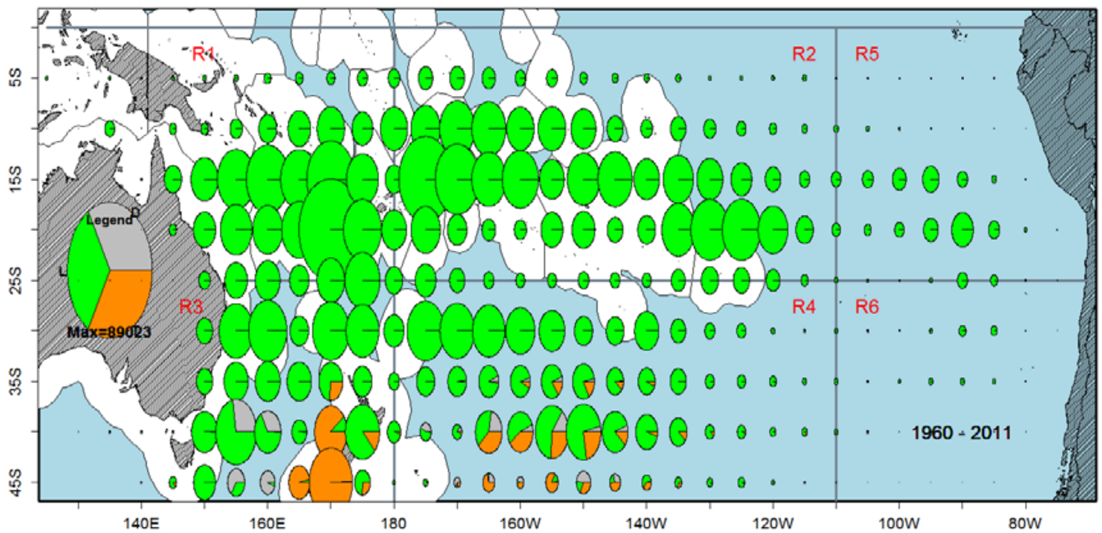


Figure 2: Map showing model regions 1 to 6, and the total catches (1960 to 2011) by 5° squares of latitude and longitude by the longline, troll, and driftnet fisheries.

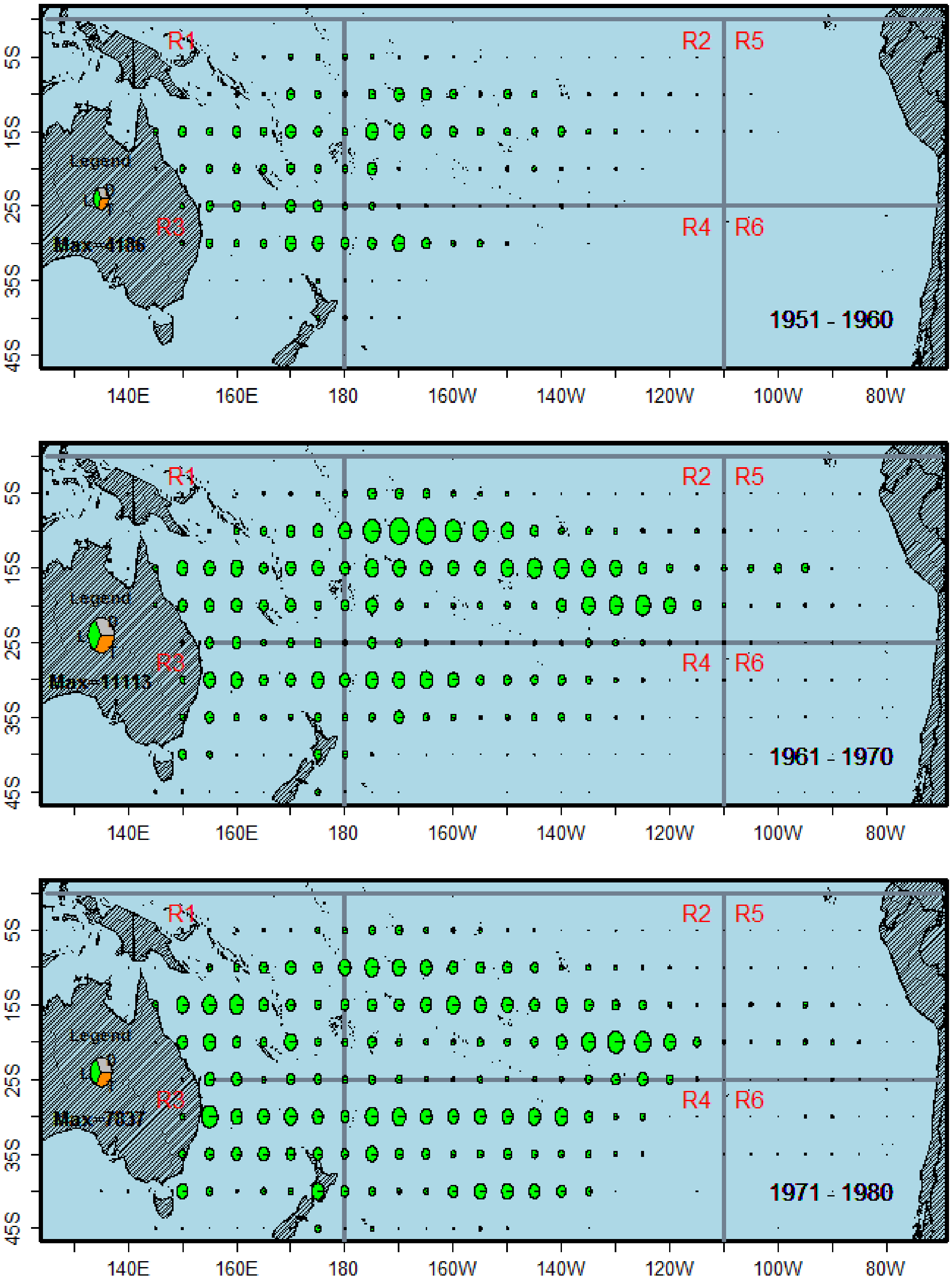


**Figure 3a: Total catch by decade by 5°-squares of latitude and longitude by fishing gear: longline (L), driftnet (G), and troll (T). The area of the pie chart is proportional to the total catch. The boundary of the stock assessment area is delineated by the black line and regional boundaries are delineated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

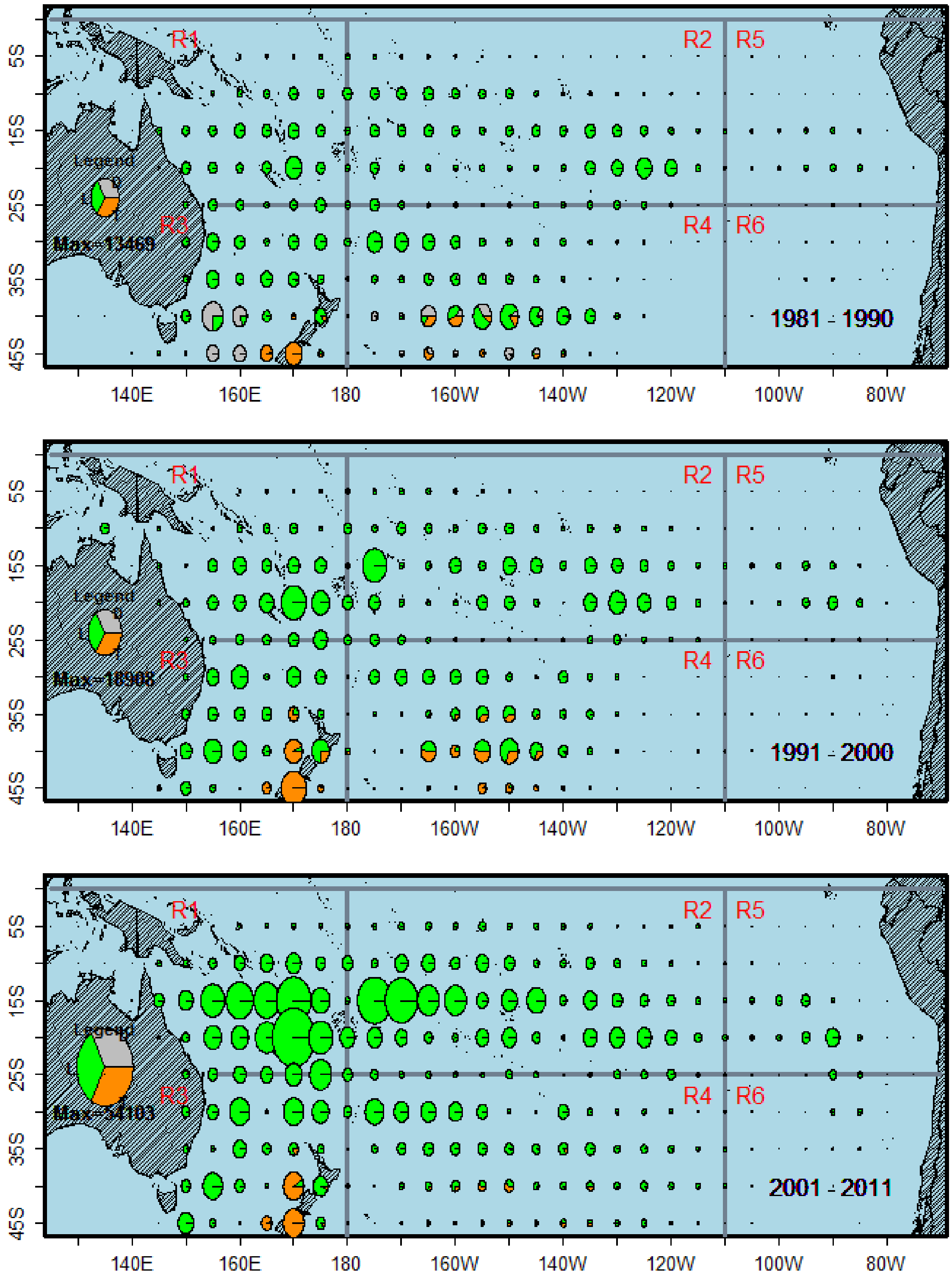


**Figure 3b: Total catch by decade by 5°-squares of latitude and longitude by fishing gear: longline (L), driftnet (G), and troll (T). The area of the pie chart is proportional to the total catch. The boundary of the stock assessment area is delineated by the black line and regional boundaries are delineated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

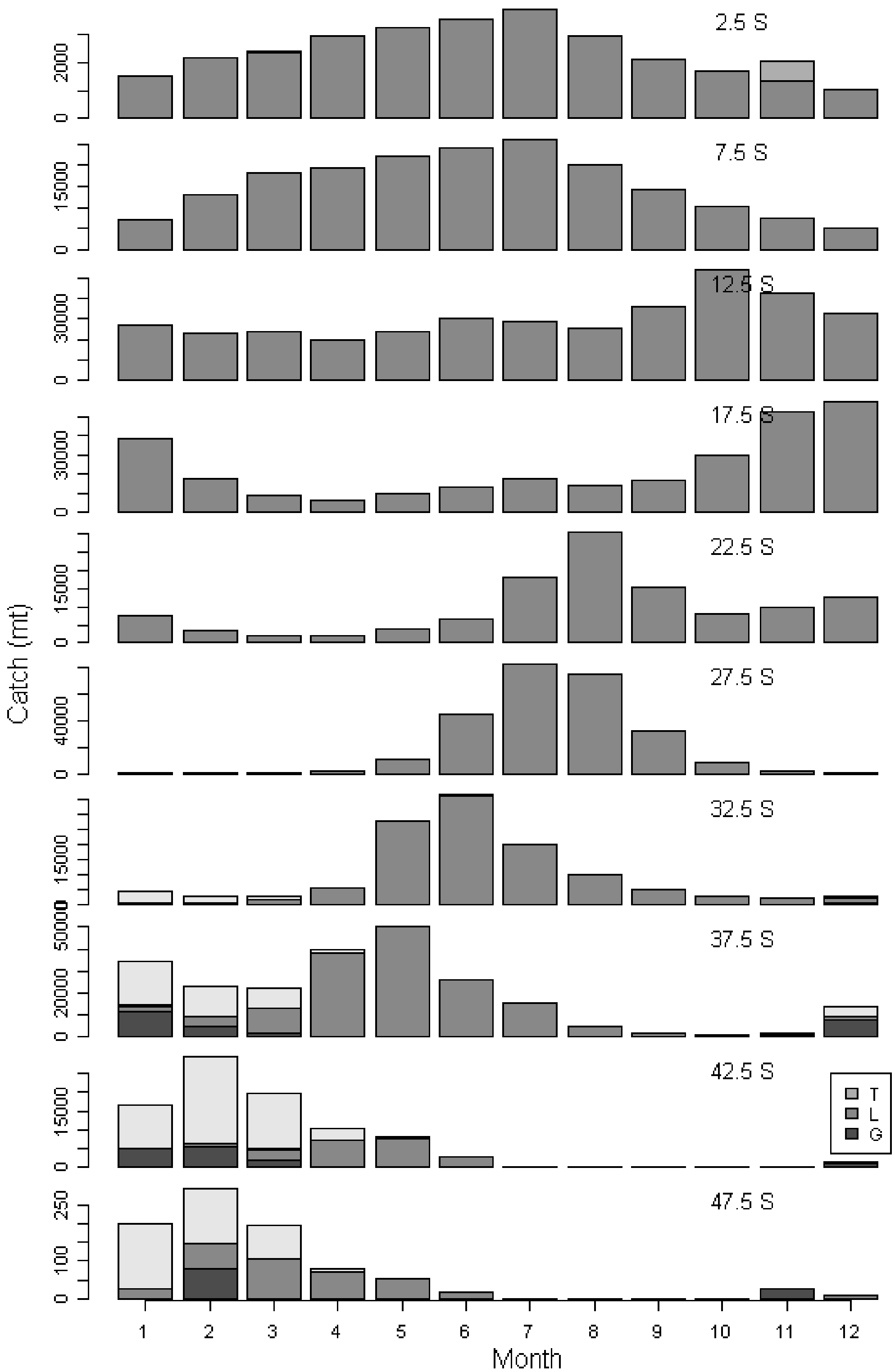


**Figure 4: Cumulative monthly distribution of South Pacific albacore catch by gear (T=troll, L= longline, G=drift net) by 5° latitudinal band for 1980 to 2003 combined.**

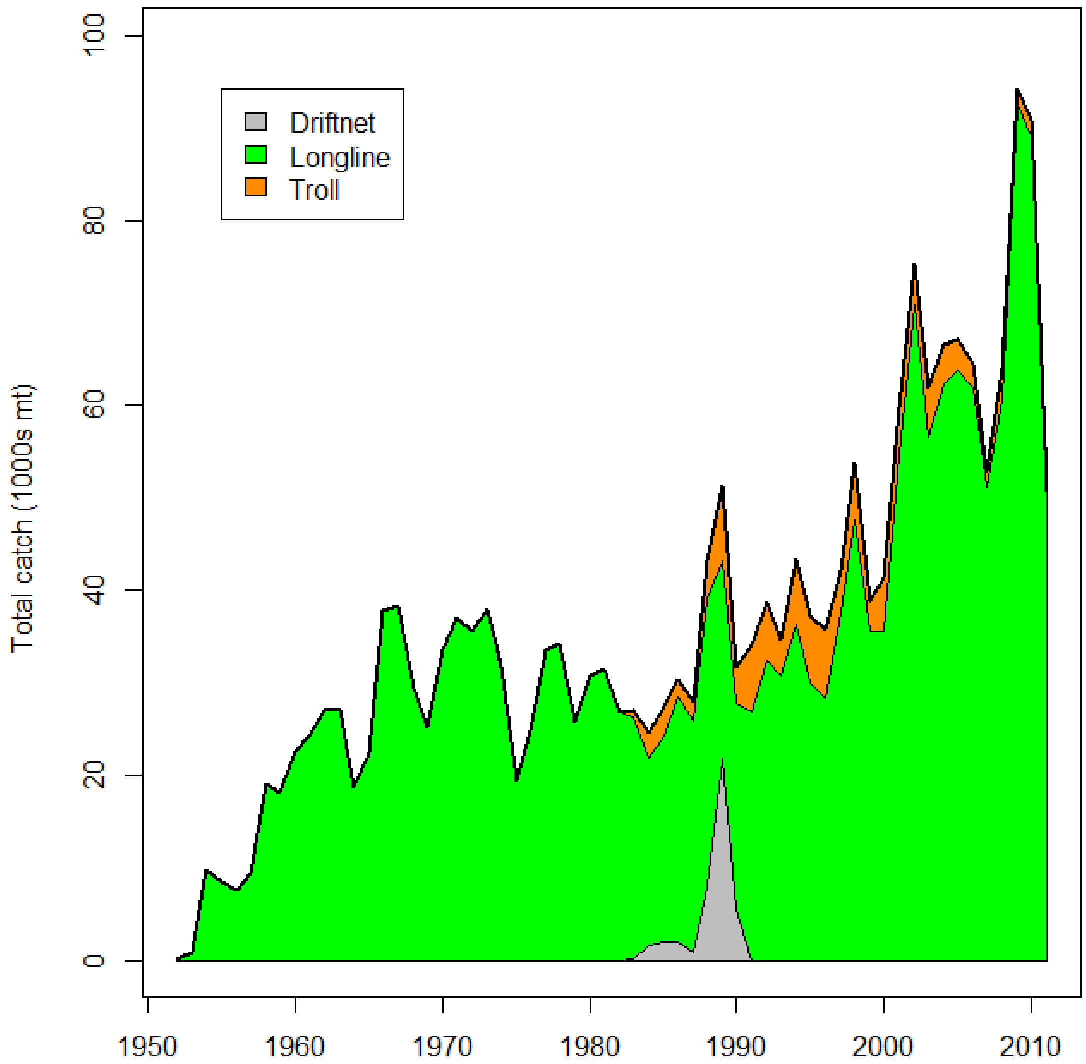


**Figure 5: Total annual catch (mt) of South Pacific albacore by fishing method for 1952 to 2011.**

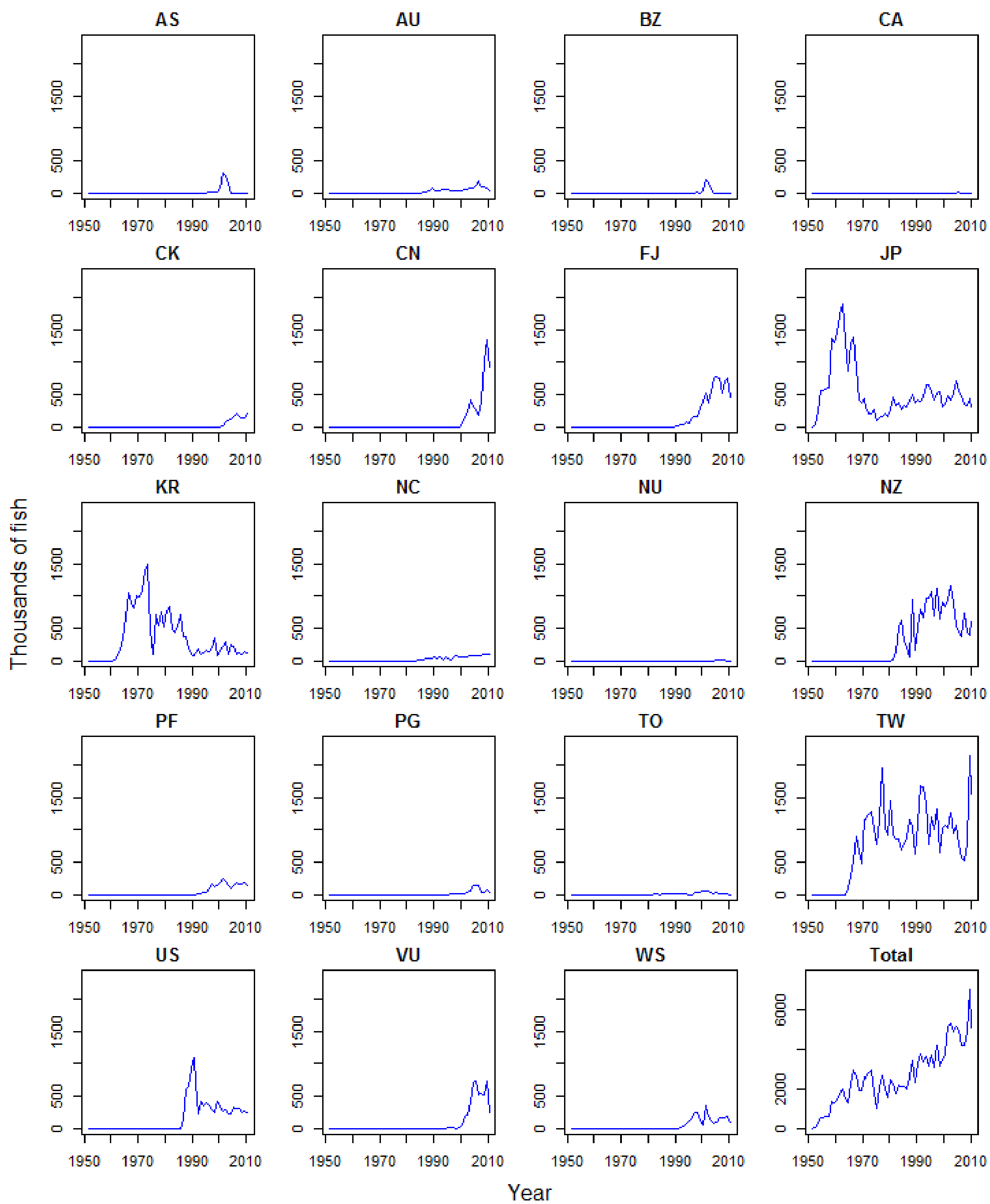


**Figure 6: Annual catches by flag for the flags with the most cumulative catch (catches in thousands of fish). Driftnet catches are not included.**

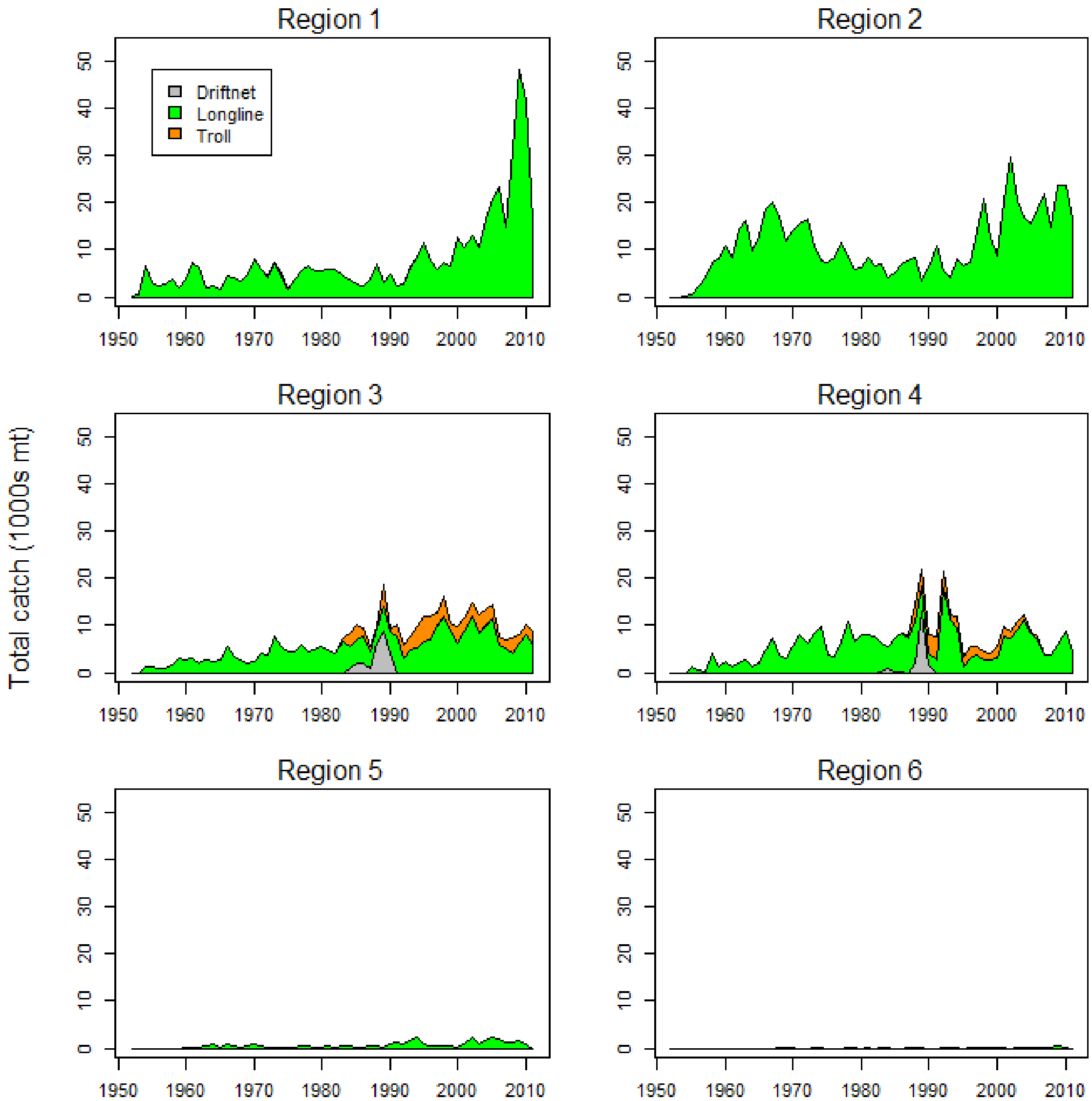


**Figure 7: Total annual catch (mt) of South Pacific albacore by fishing method and region for 1952 to 2011.**


**Figure 8: Cumulative albacore catch by fishery by 5°-square of latitude and longitude from 1970 to 2011. The circle size is proportional to the cumulative catch (maximum circle size corresponds to 41,000 mt). Grey lines represent regional boundaries.**

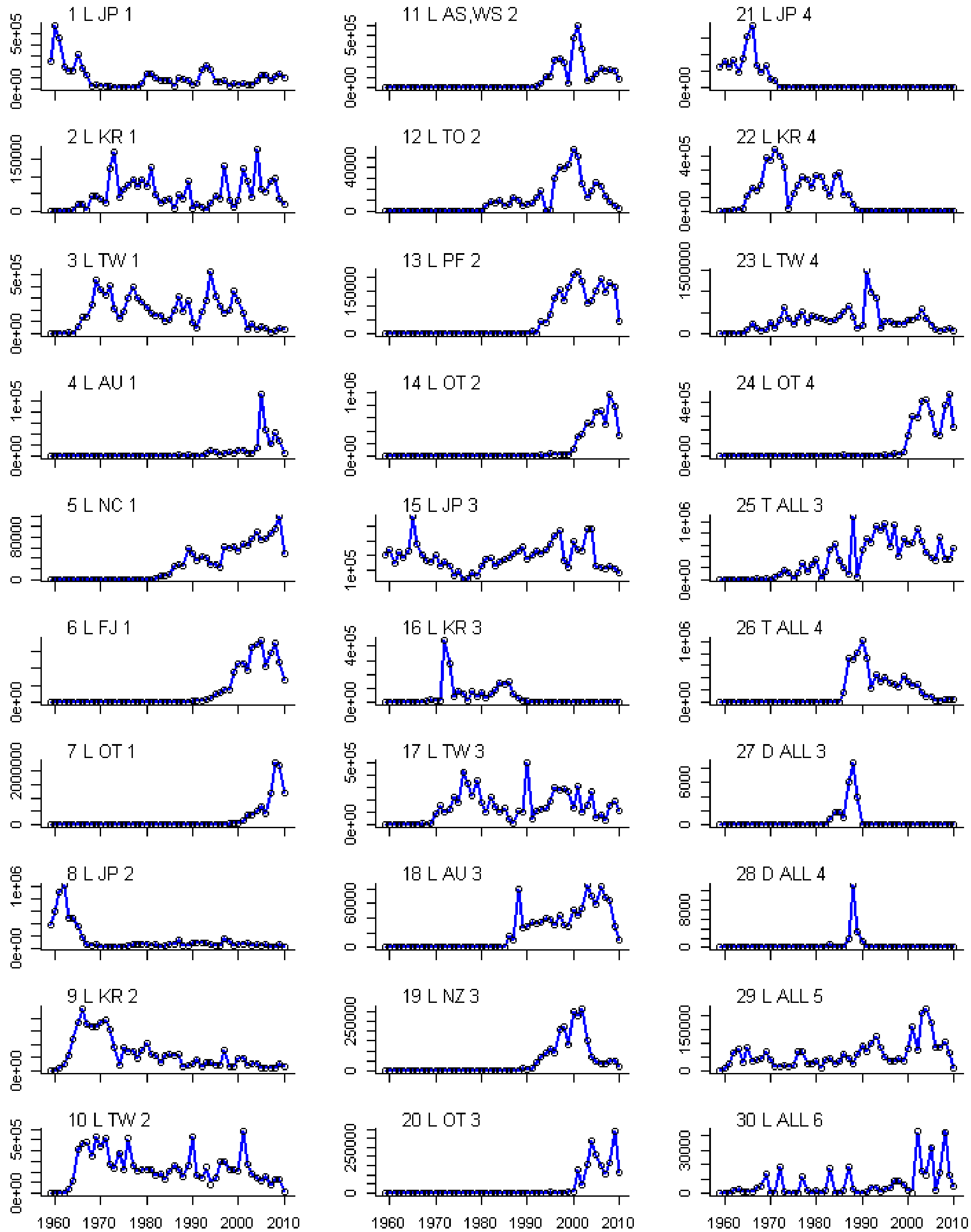


**Figure 9: Annual catches (observed) by fishery (catches in thousands of fish for all fisheries except driftnet).**

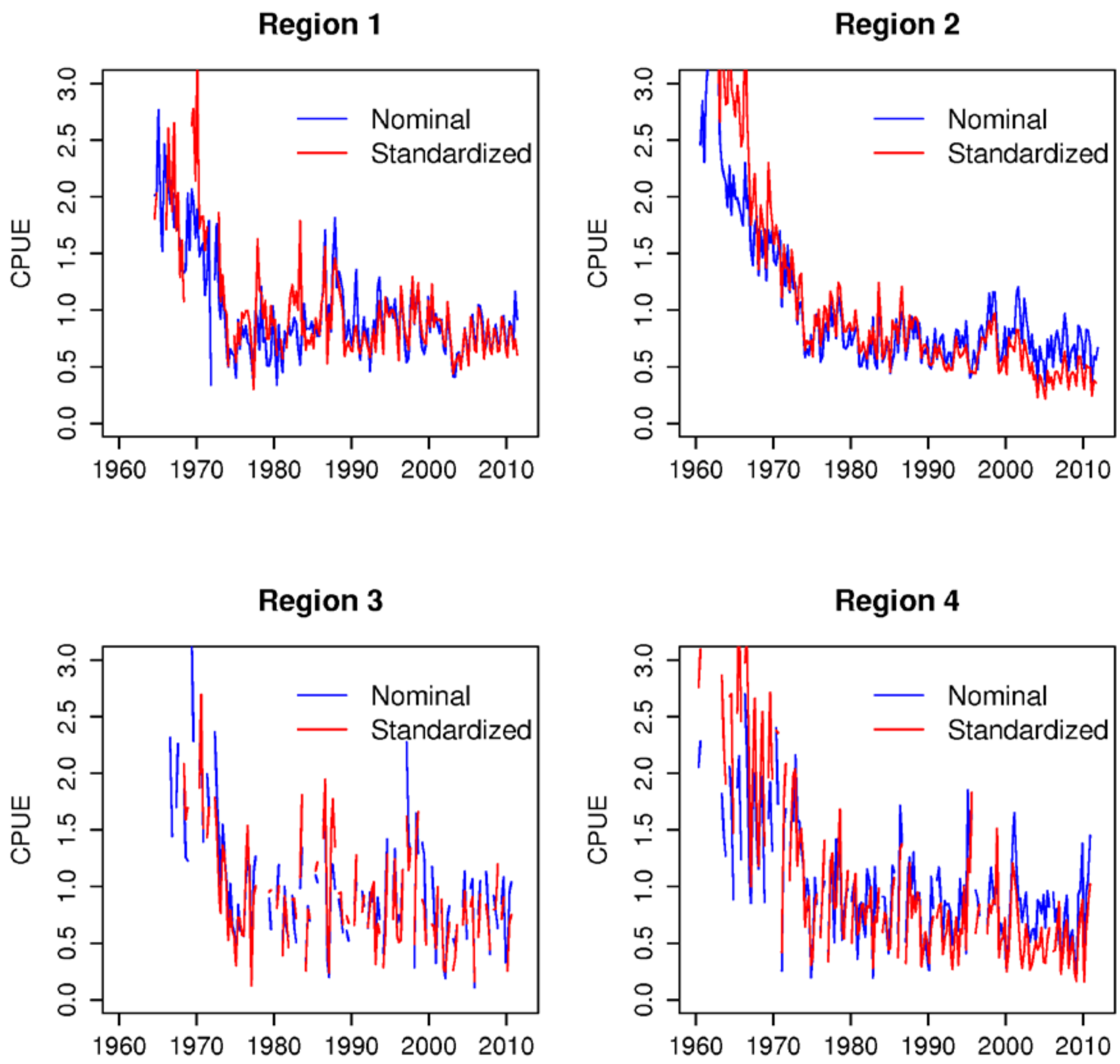


**Figure 10a: Nominal and standardized CPUE for south Pacific albacore by region, from Bigelow and Hoyle (2012).**

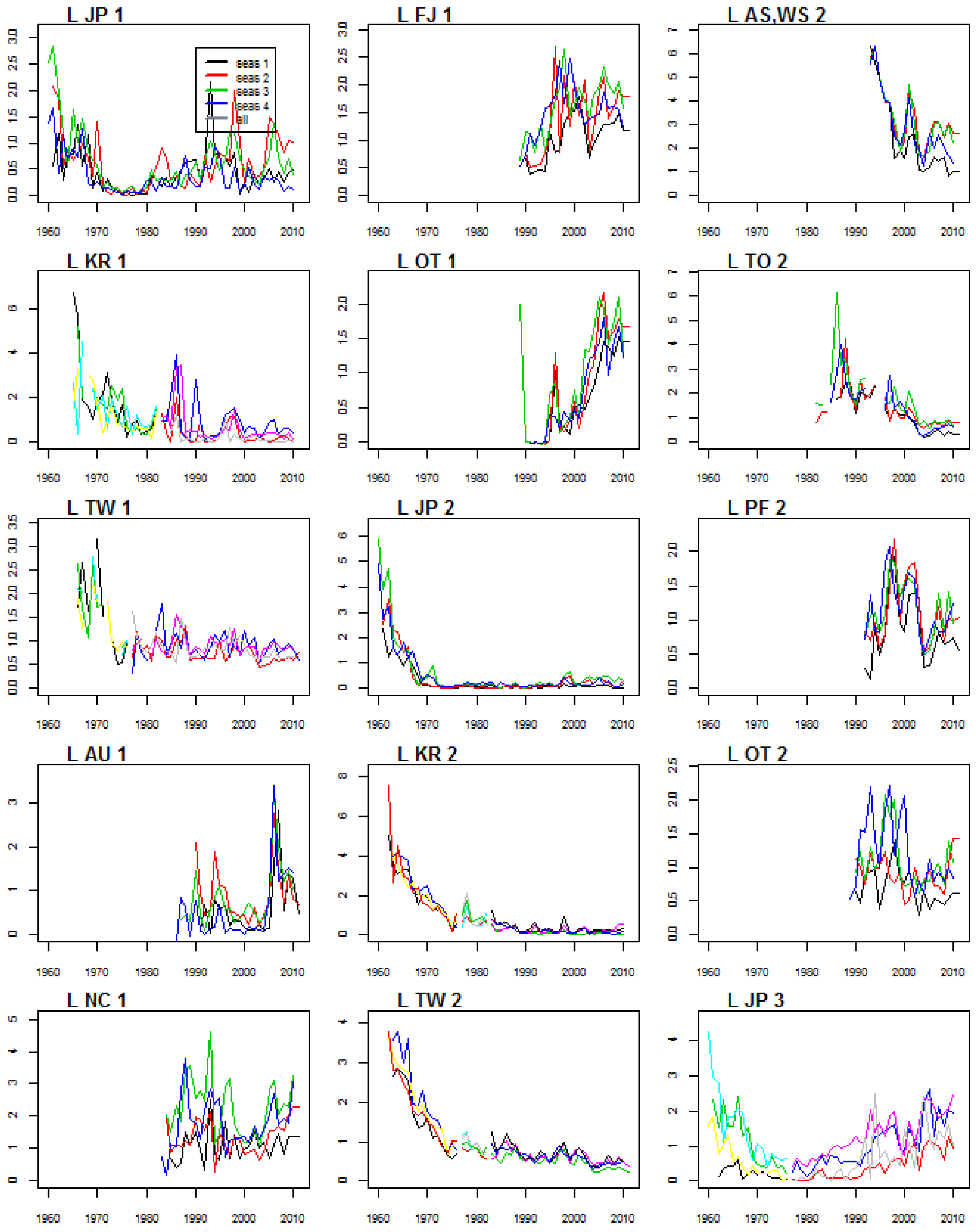


**Figure 10b: Annual average catch rates by fishery. Catch rates for standardised fisheries (all JP, KR, and TW) have no units. Non-standardised longline fisheries are expressed as number per 100 hooks; troll are expressed as number per vessel days fished; drift net are expressed as mt per day.**

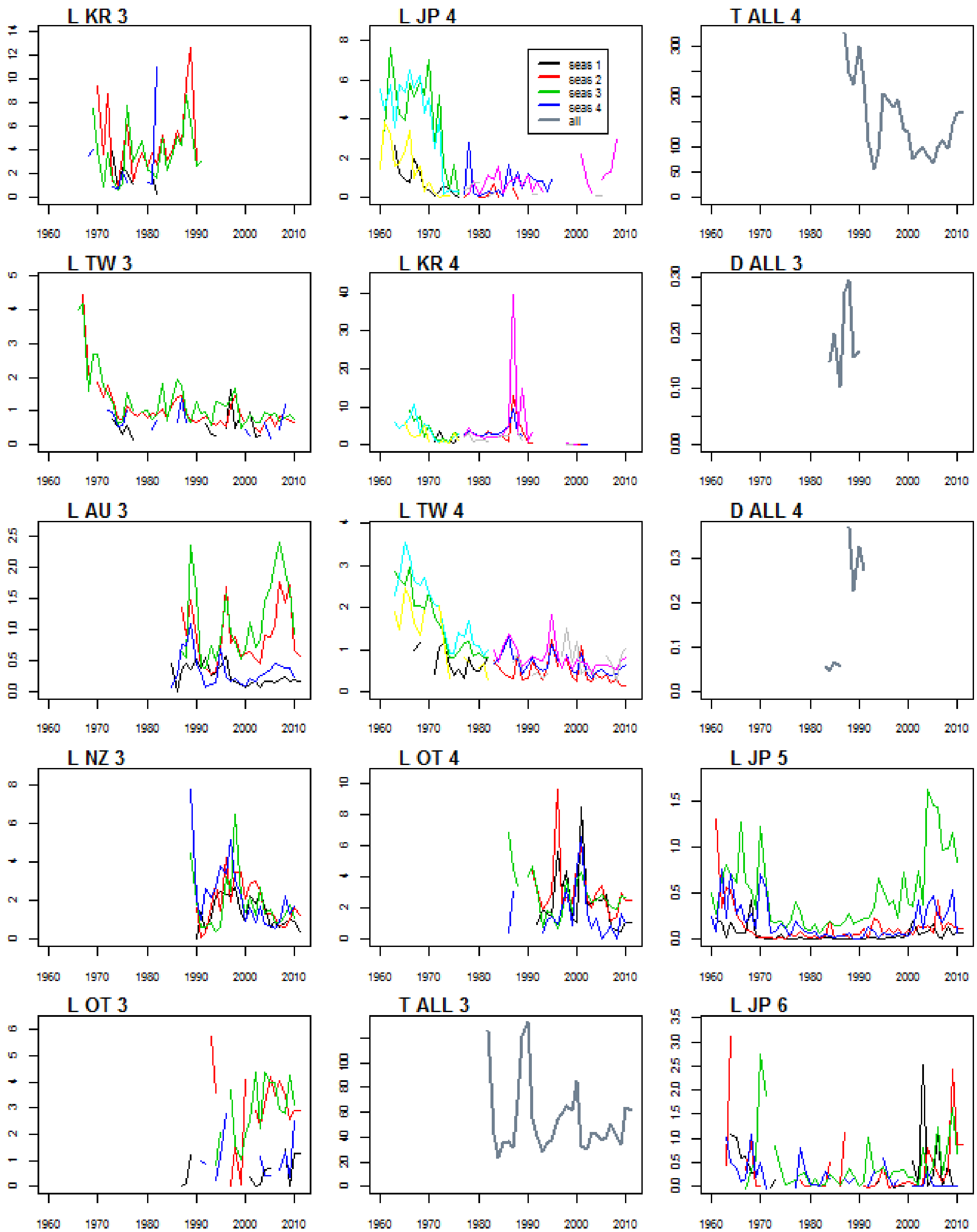


**Figure 10c: Annual average catch rates by fishery. Catch rates for standardised fisheries (all JP, KR, and TW) have no units. Non-standardised longline fisheries are expressed as number per 100 hooks; troll are expressed as number per vessel days fished; drift net are expressed as mt per day.**

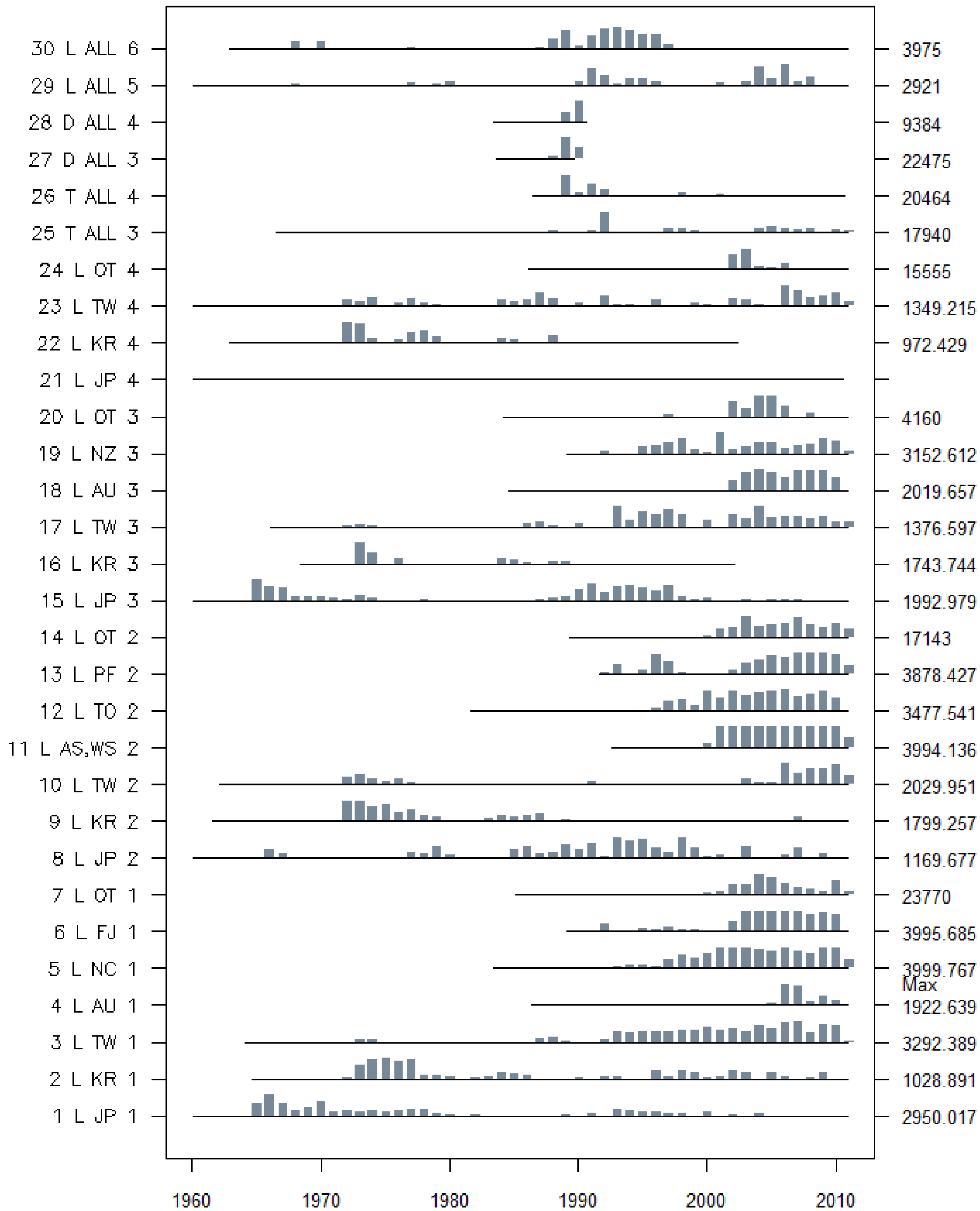


**Figure 11: Length-frequency samples by fishery and year. The number on the right vertical-axis represents the maximum number of fish measured in a single year for the fishery. Frequency histograms are scaled relative to the maximum value for the fishery. The length of the x-axis denotes the period of catch and effort data from the fishery. No size frequency data were available before 1960.**

**Figure 12: Tag releases (bars) and recoveries (line) by quarter for the South Pacific albacore fishery.**

**Figure 13: 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.**

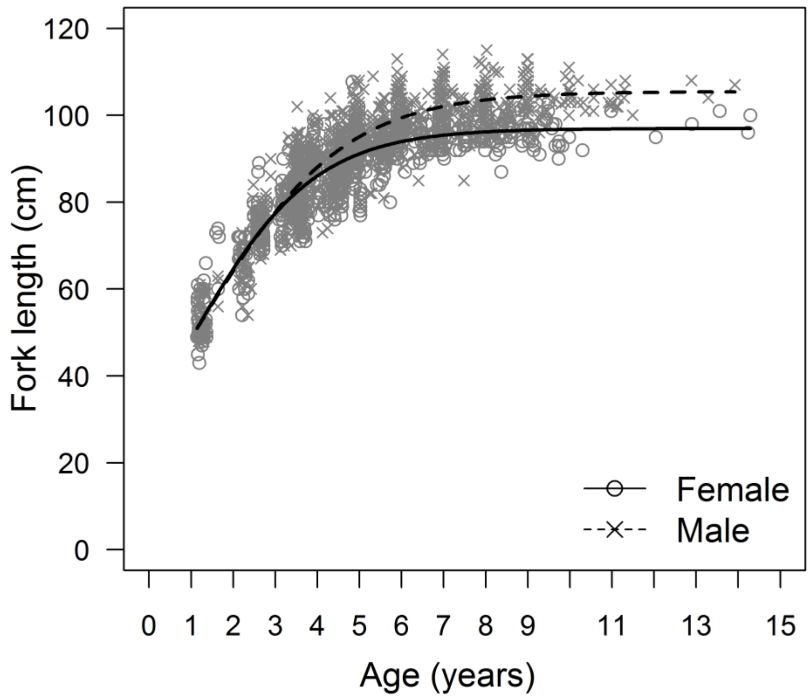


**Figure 14: Length-at-age data and logistic growth models for female and male South Pacific albacore. (From Williams *et al.* 2012).**

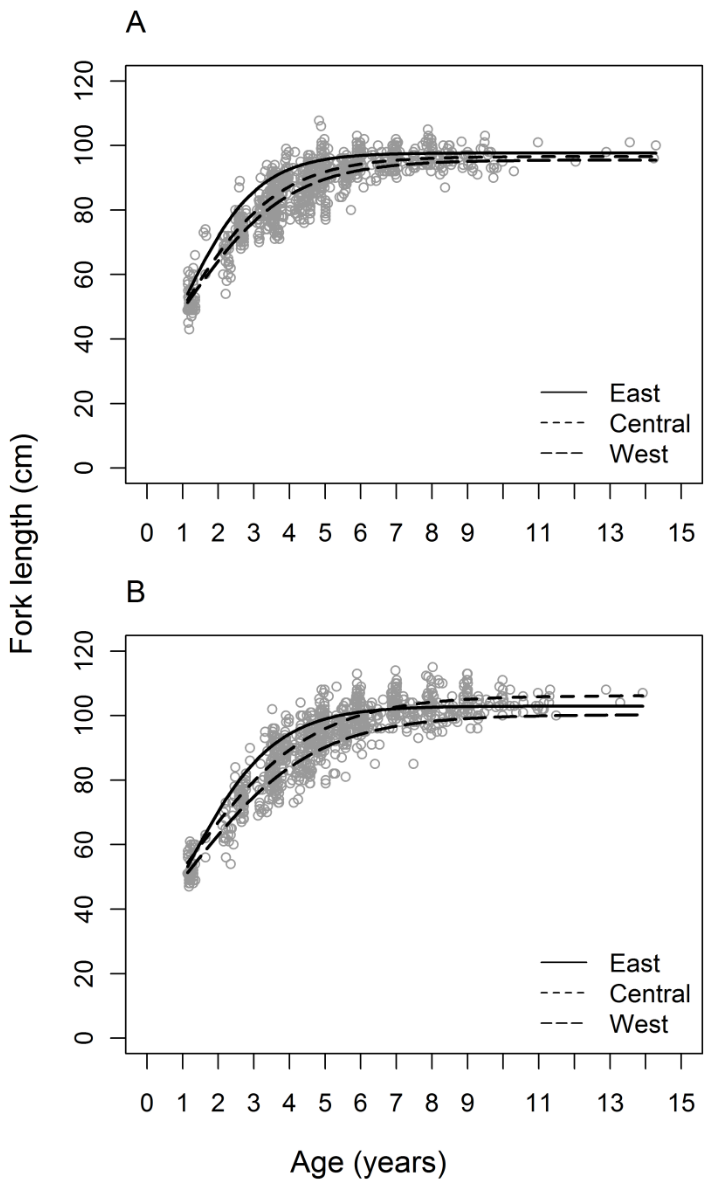


**Figure 15: Predicted growth curves for females (above) and males (below) in the west (150°E), central (185°E) and east (220°E) South Pacific Ocean. (From Williams *et al*. 2012).**

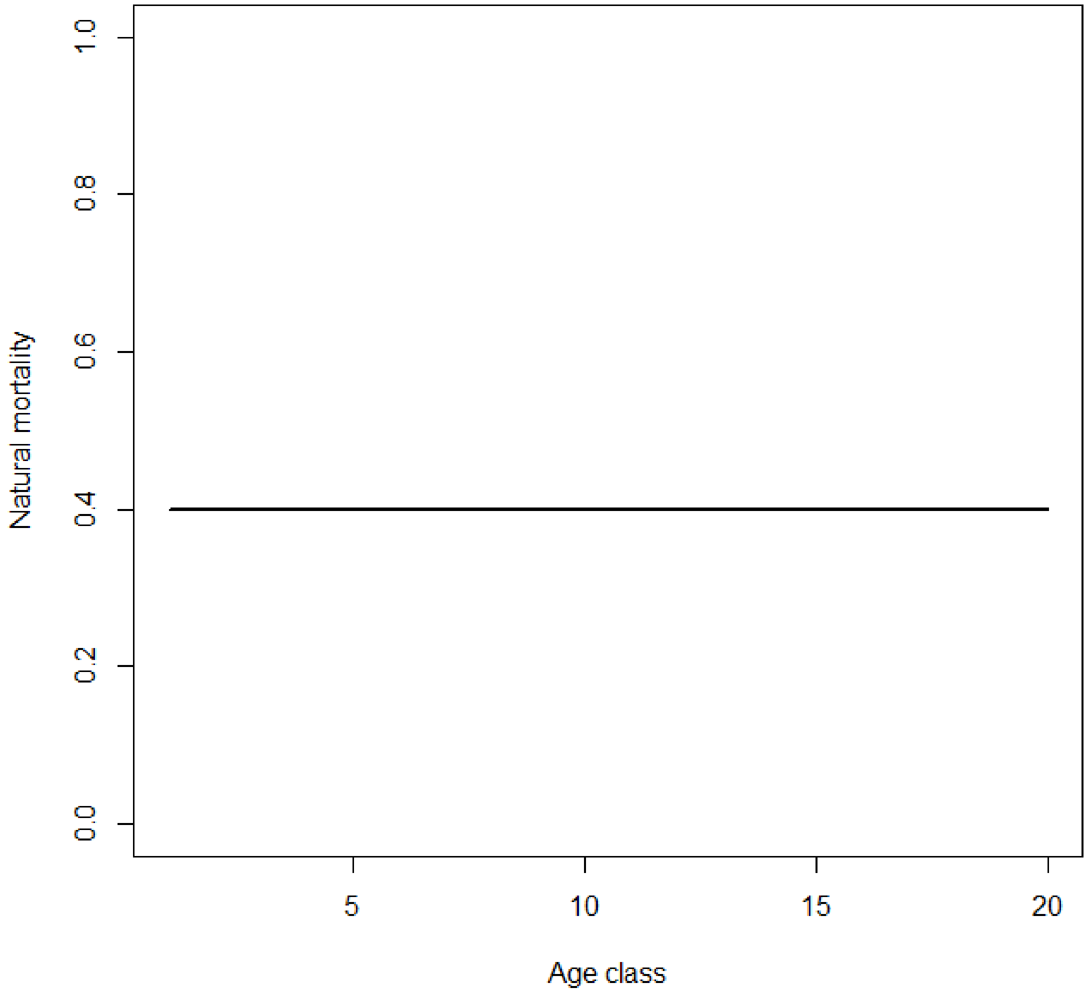


**Figure 16: Natural mortality at age.**

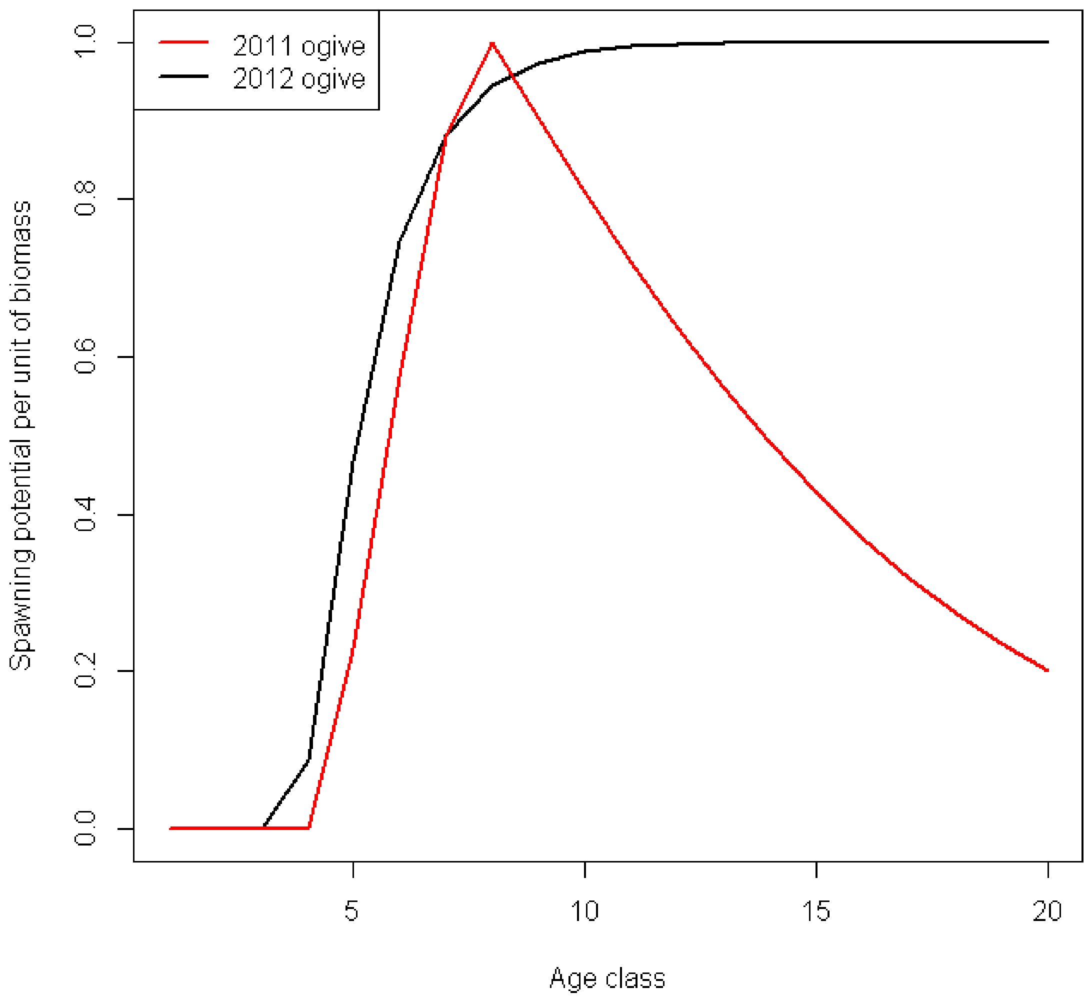


**Figure 17: Spawning potential per unit of population biomass, at age. The 2012 ogive is based on new data from a study of south Pacific albacore. The 2011 ogive declined after age 8 because female natural mortality was assumed to increase after maturity.**

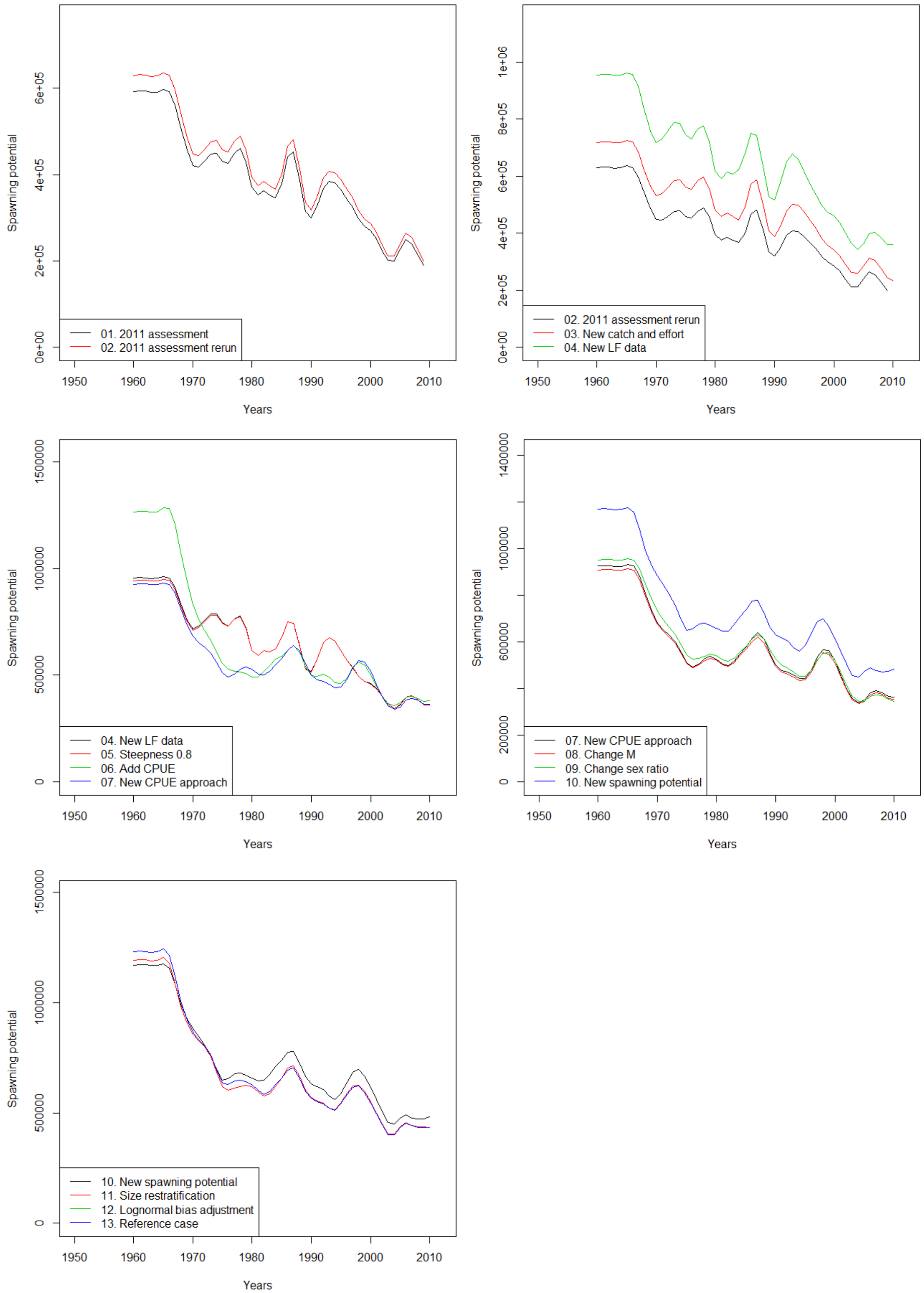


Figure 18: Spawning potential through time for stages of model development from the 2011 assessment to the 2012 reference case.

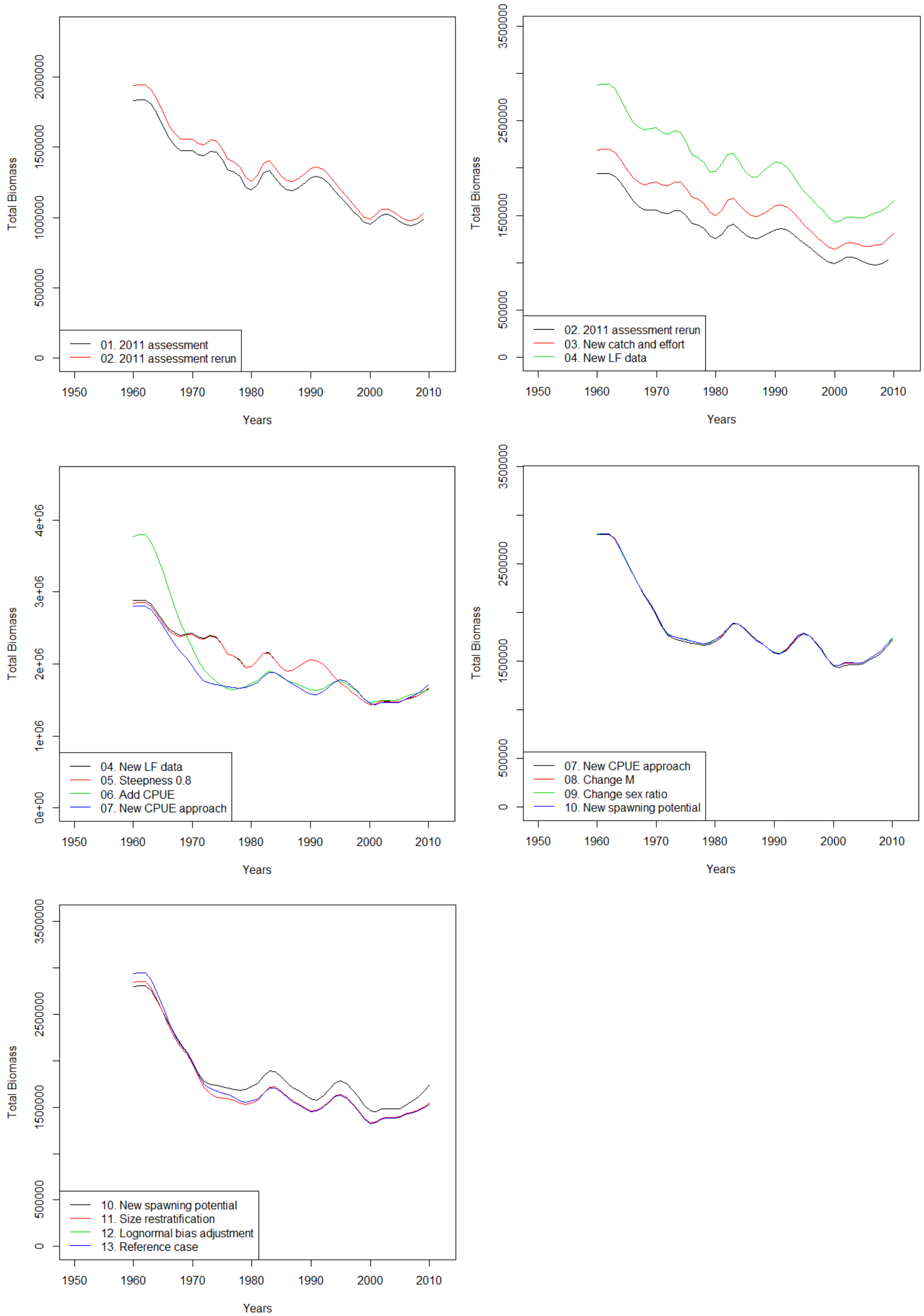


Figure 19: Biomass through time for stages of model development from the 2011 assessment to the 2012 reference case.

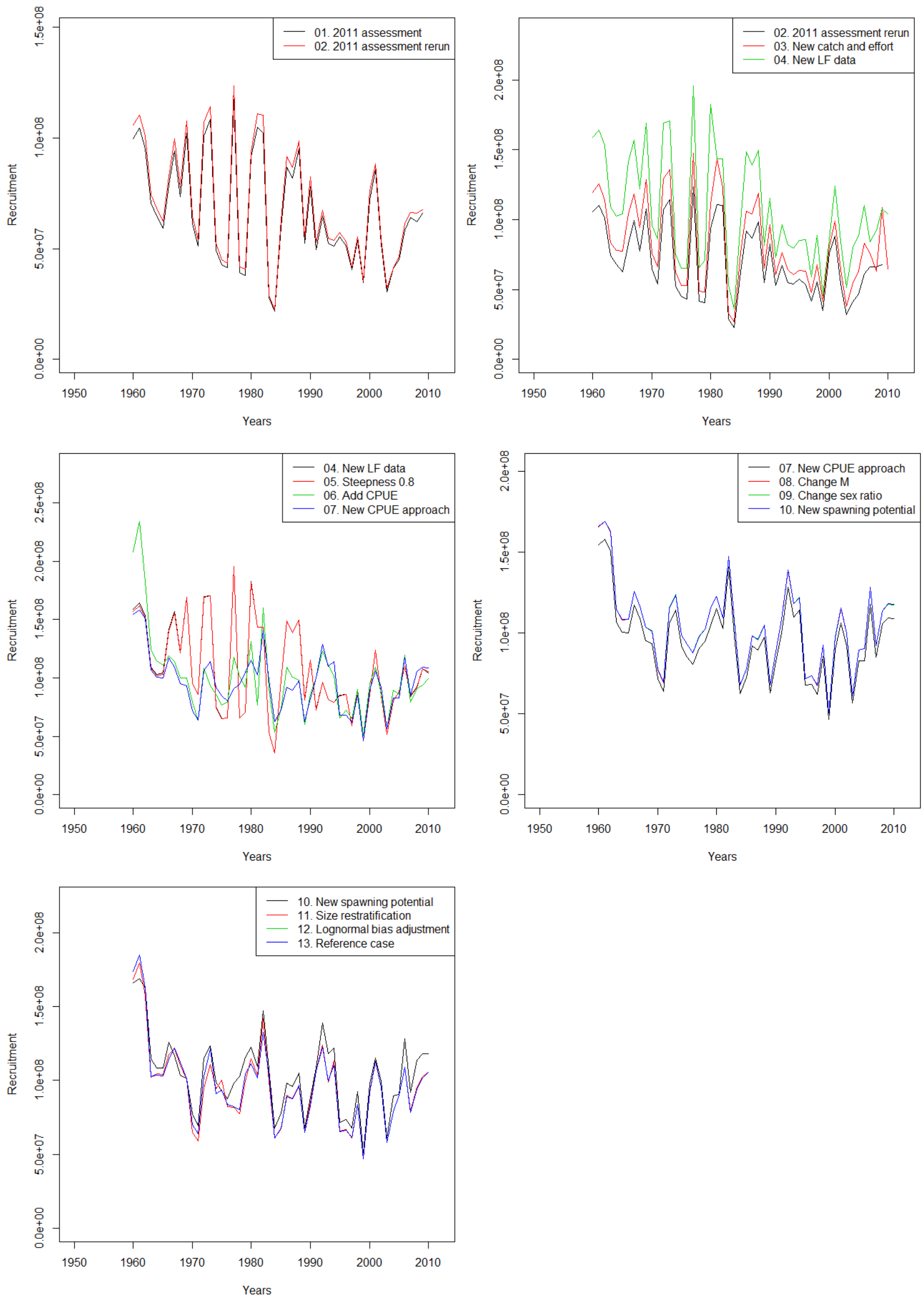


Figure 20: Recruitment through time for stages of model development from the 2011 assessment to the 2012 reference case.

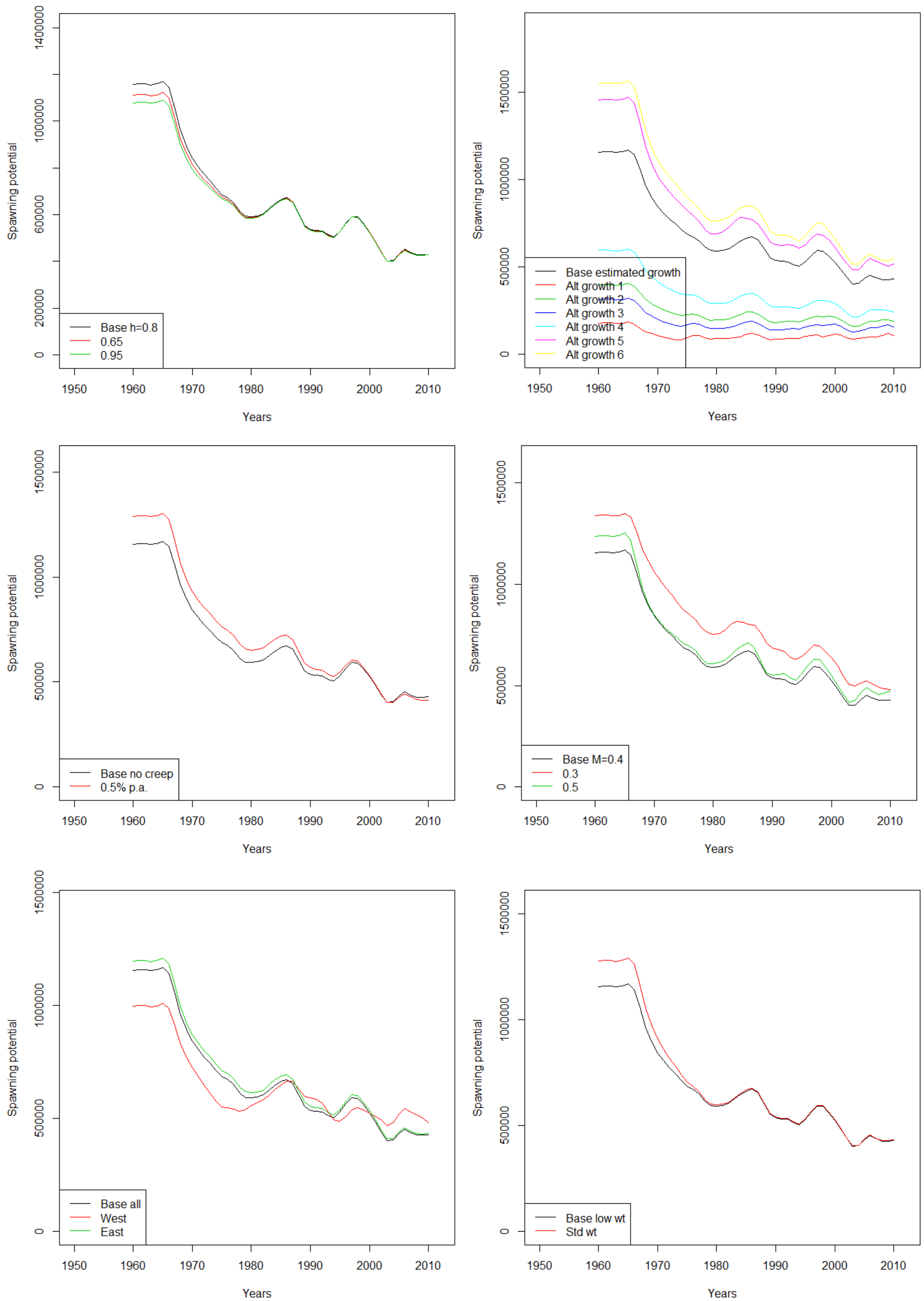


Figure 21: Spawning potential through time under alternative structural assumptions about 1) steepness, 2) growth, 3) effort creep, 4) natural mortality, 5) CPUE, and 6) early CPUE.

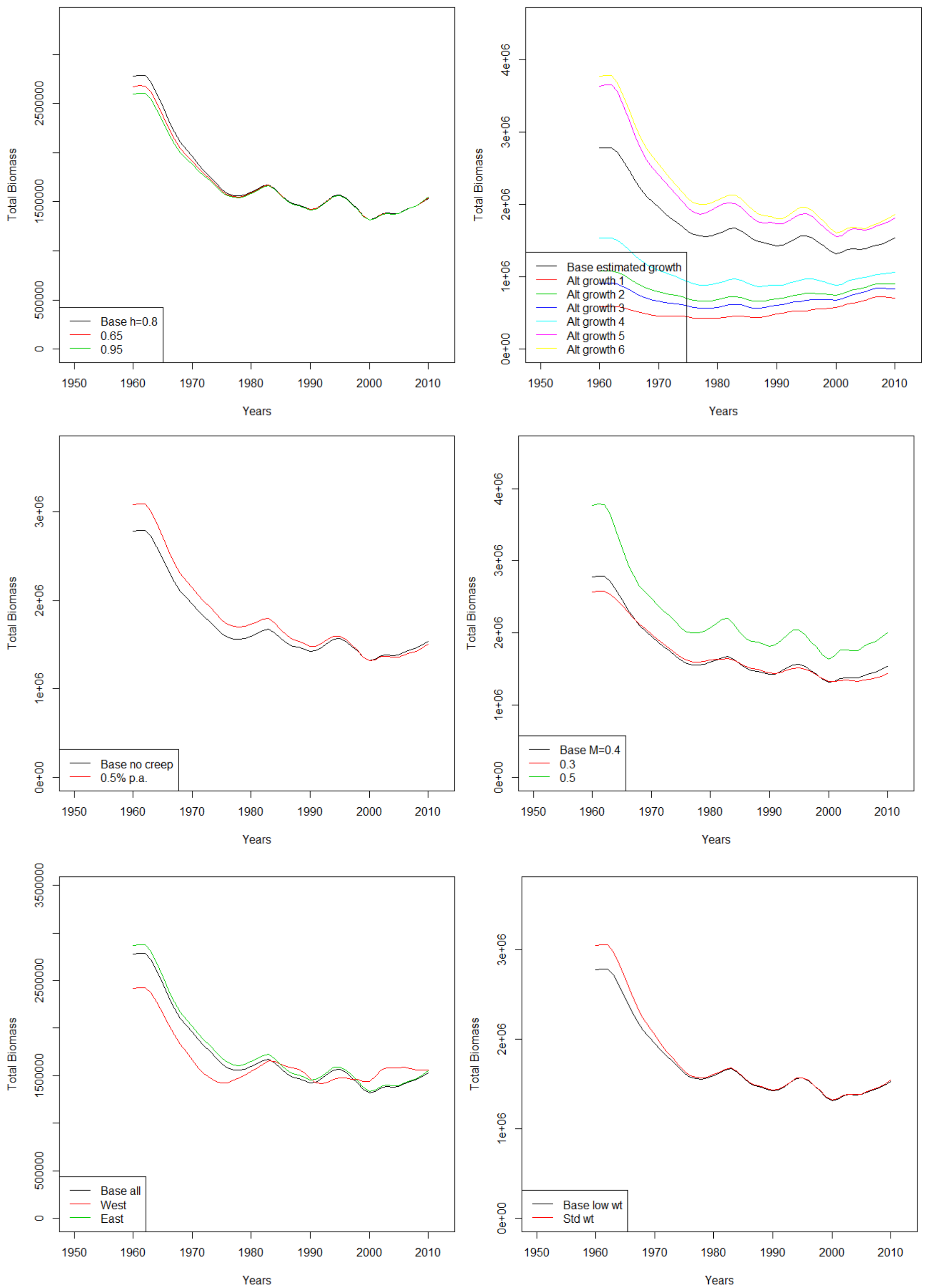


Figure 22: Total biomass through time under alternative structural assumptions about 1) steepness, 2) growth, 3) effort creep, 4) natural mortality, 5) CPUE, and 6) early CPUE.


Figure 23: Recruitment through time under alternative structural assumptions about 1) steepness, 2) growth, 3) effort creep, 4) natural mortality, 5) CPUE, and 6) early CPUE.

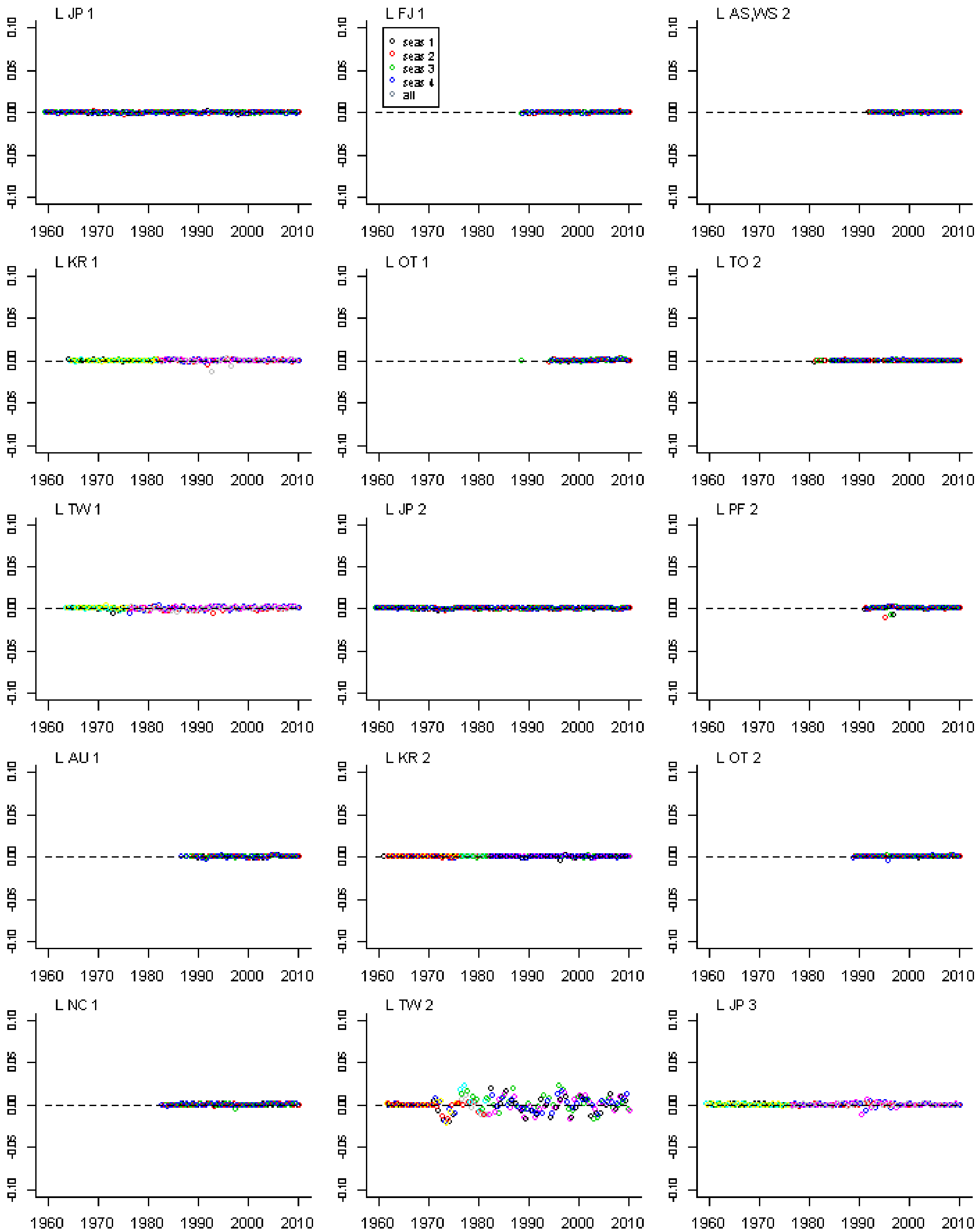


Figure 24a: Residuals of ln (total catch) for each fishery.

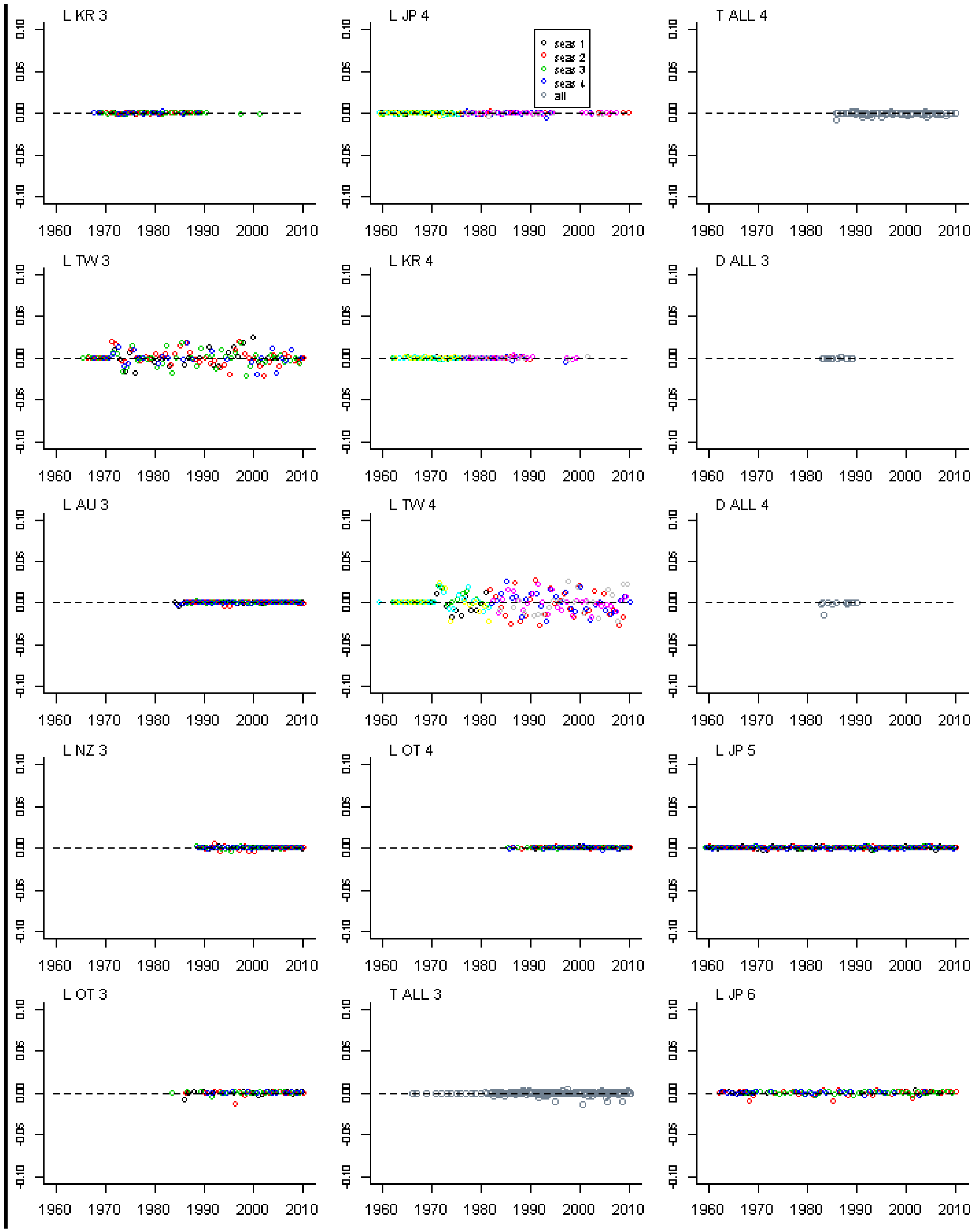


Figure 24b: Residuals of ln (total catch) for each fishery.

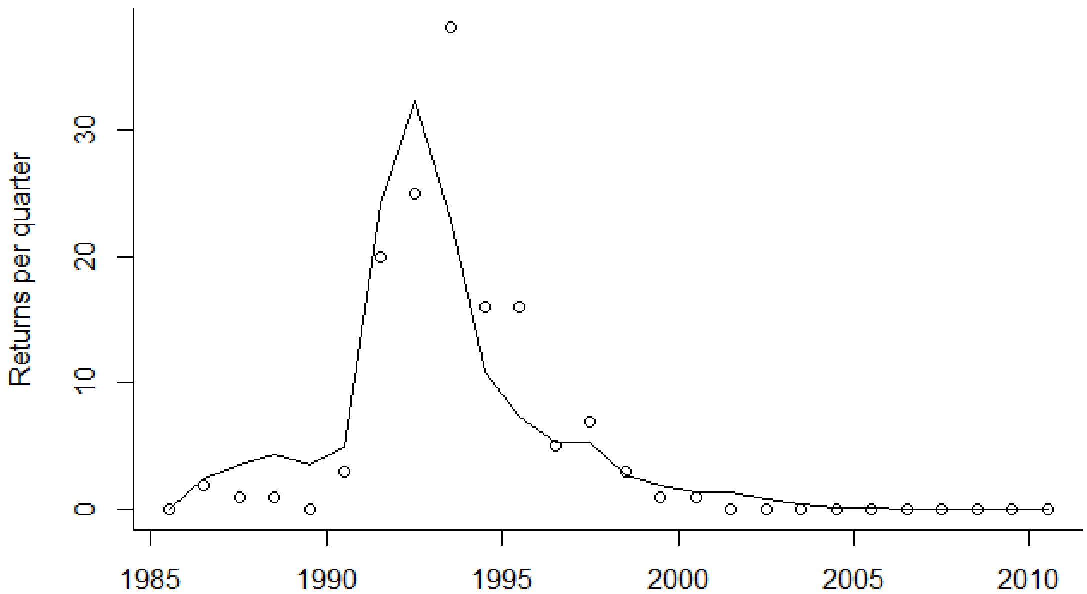


**Figure 25: A comparison of observed (points) and predicted (line) number of tag returns per quarter from the South Pacific albacore fishery.**

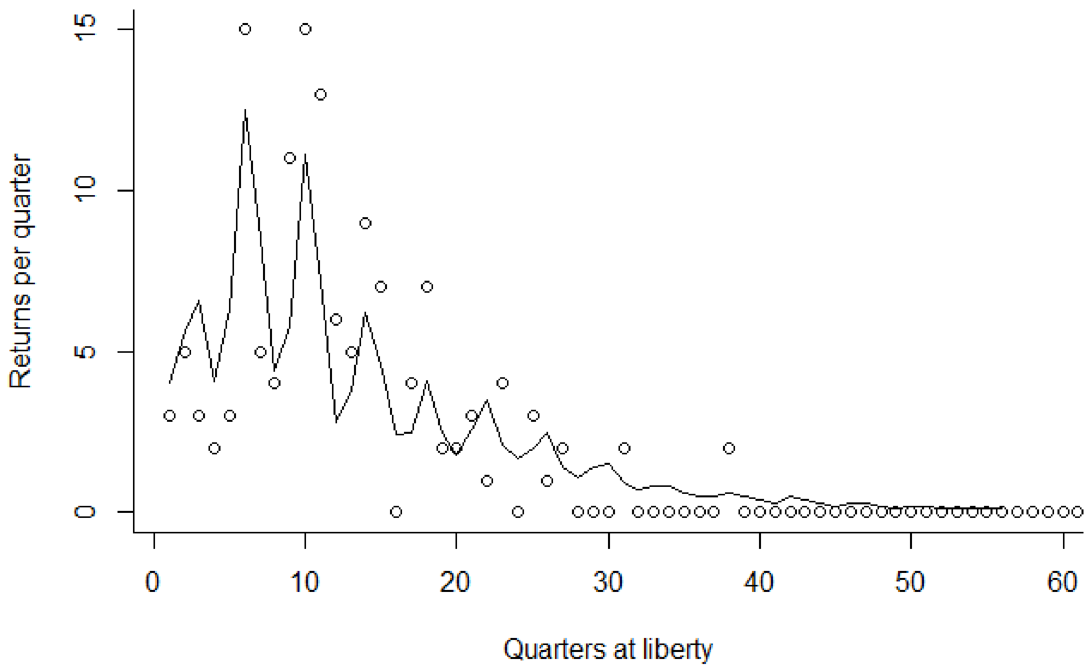


**Figure 26: A comparison of observed (points) and predicted (line) number of tag returns by period at liberty (quarters) from the South Pacific albacore fishery.**

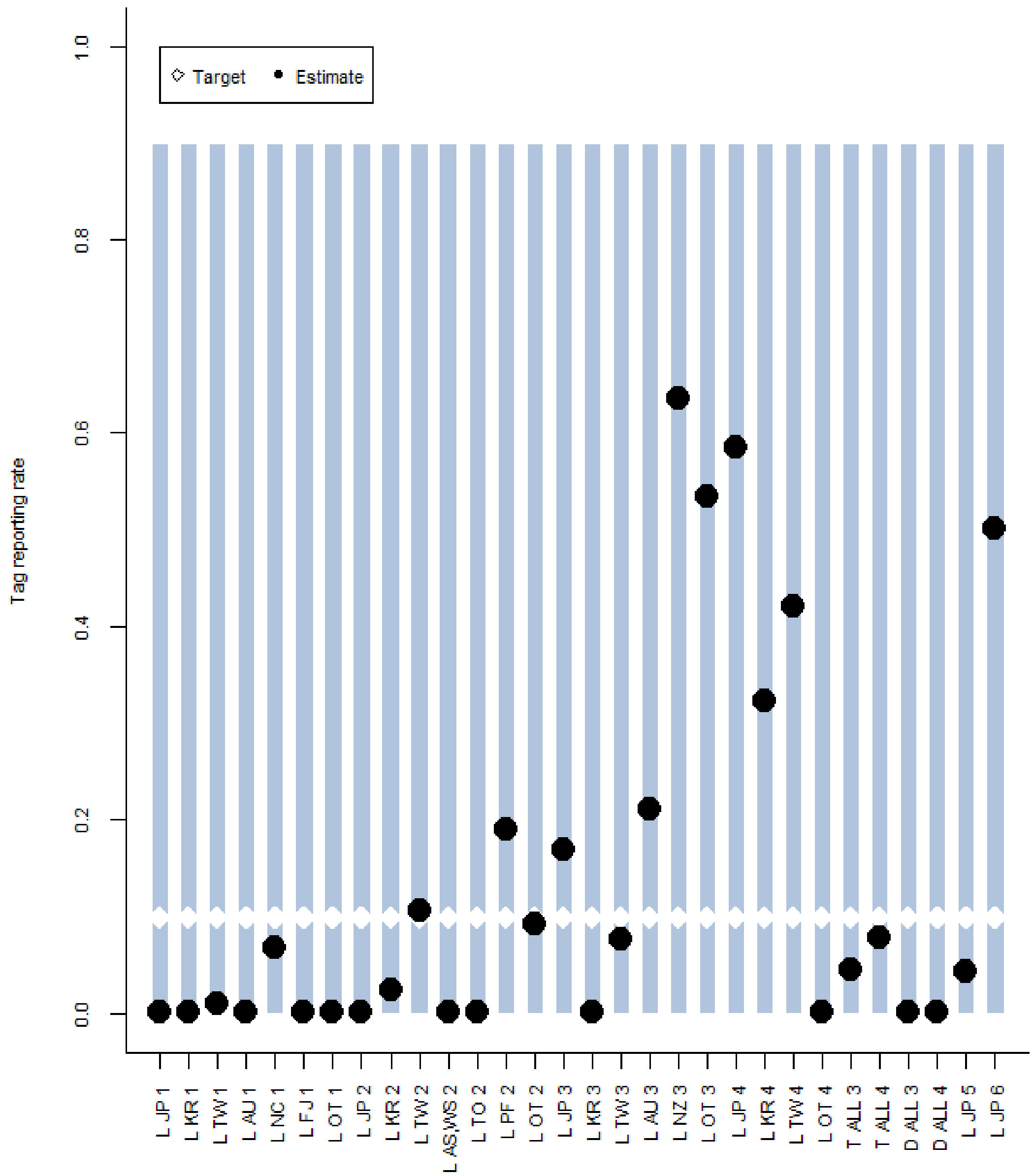


**Figure 27: Estimated tag-reporting rates by fishery (black circles). White diamonds indicate the modes of the priors for each reporting rate, and grey bars indicate a range of ±1 SD.**

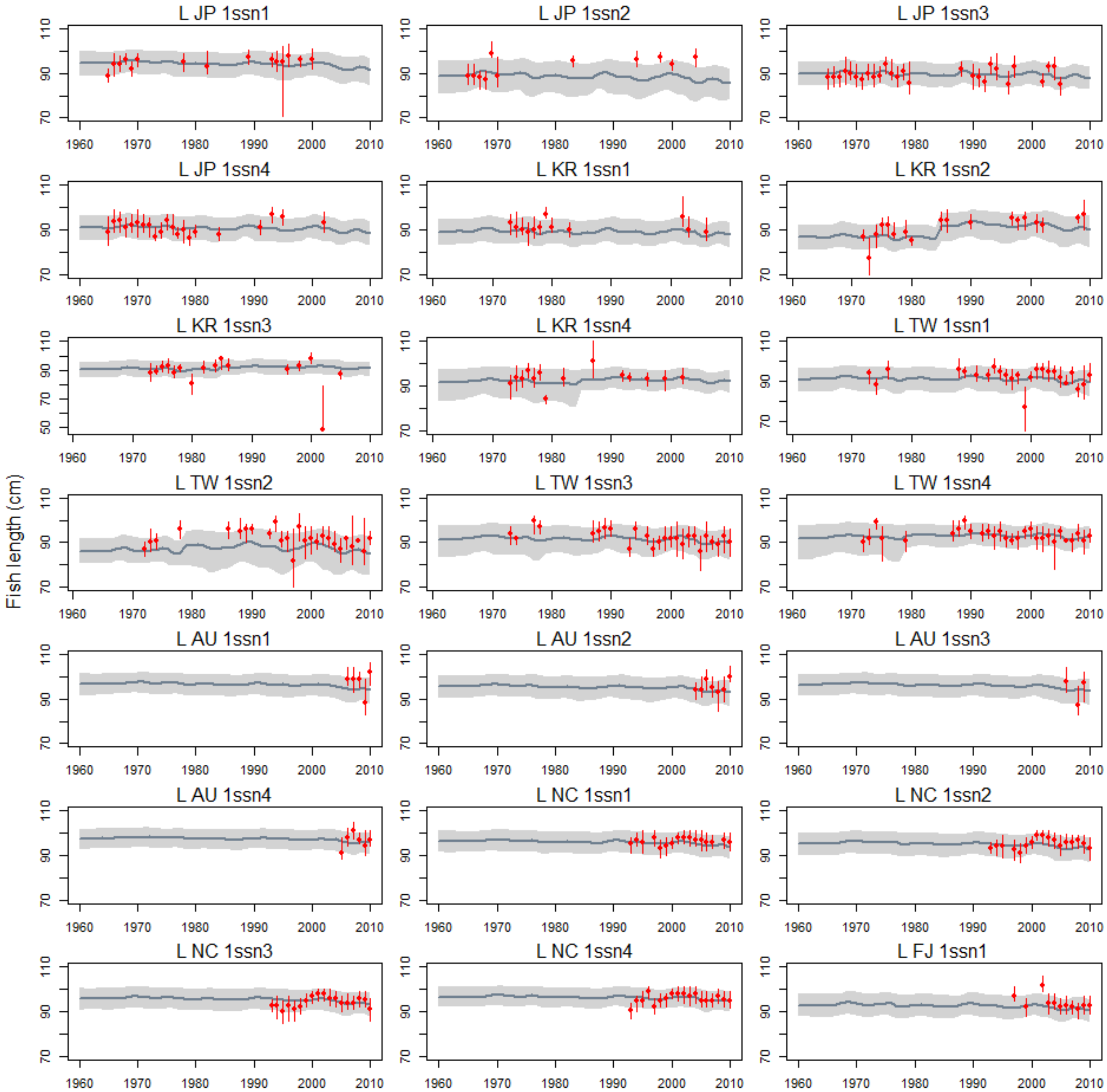


Figure 28 a: A comparison of the observed (red points) and predicted (grey line) median fish length (FL, cm) of albacore tuna by fishery for the main fisheries with length data. 'ssn' represents season. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated by year and only length samples with a minimum of 30 fish per year are plotted.

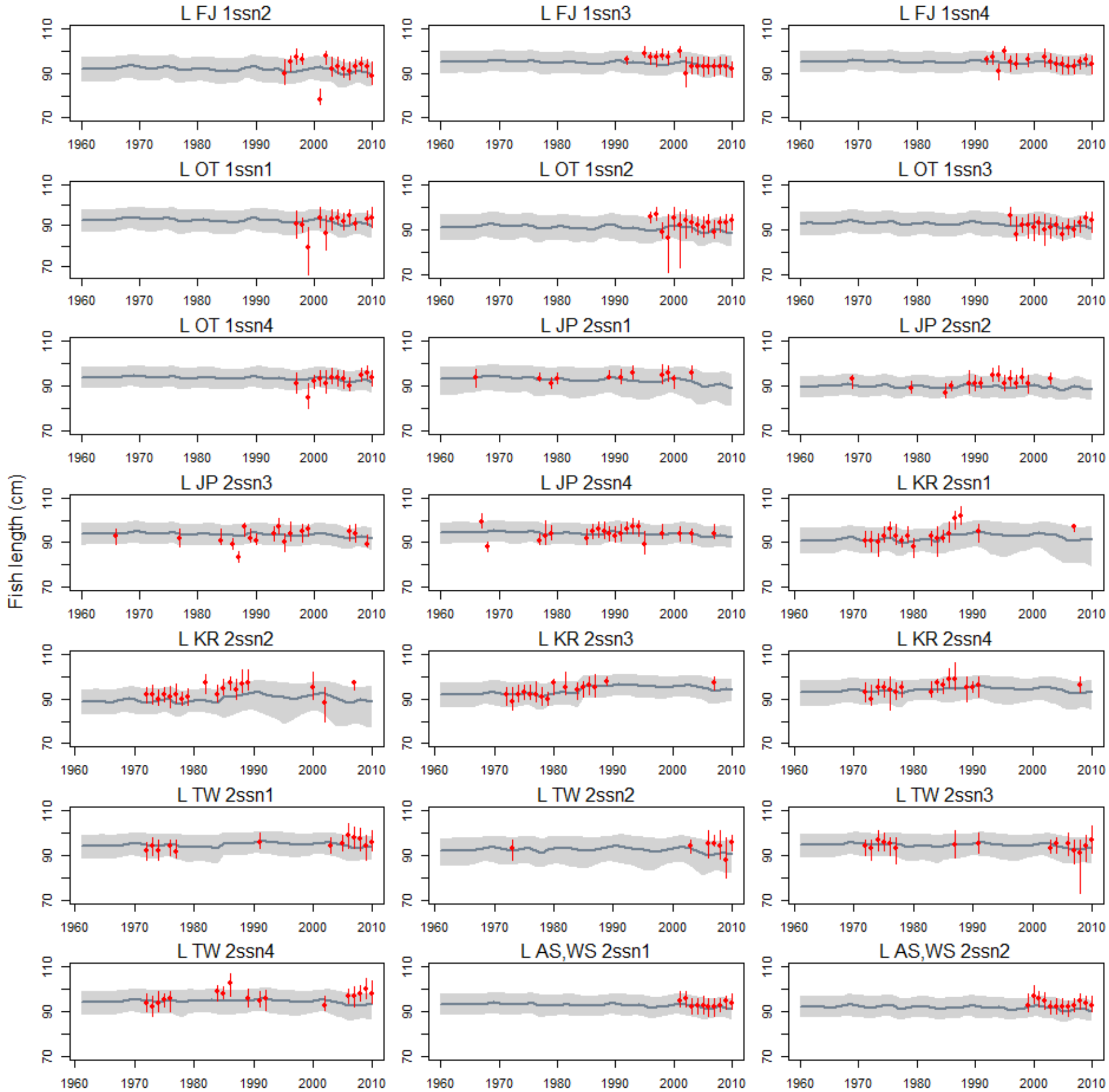


Figure 28b: A comparison of the observed (red points) and predicted (grey line) median fish length (FL, cm) of albacore tuna by fishery for the main fisheries with length data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated by year and only length samples with a minimum of 30 fish per year are plotted**.**

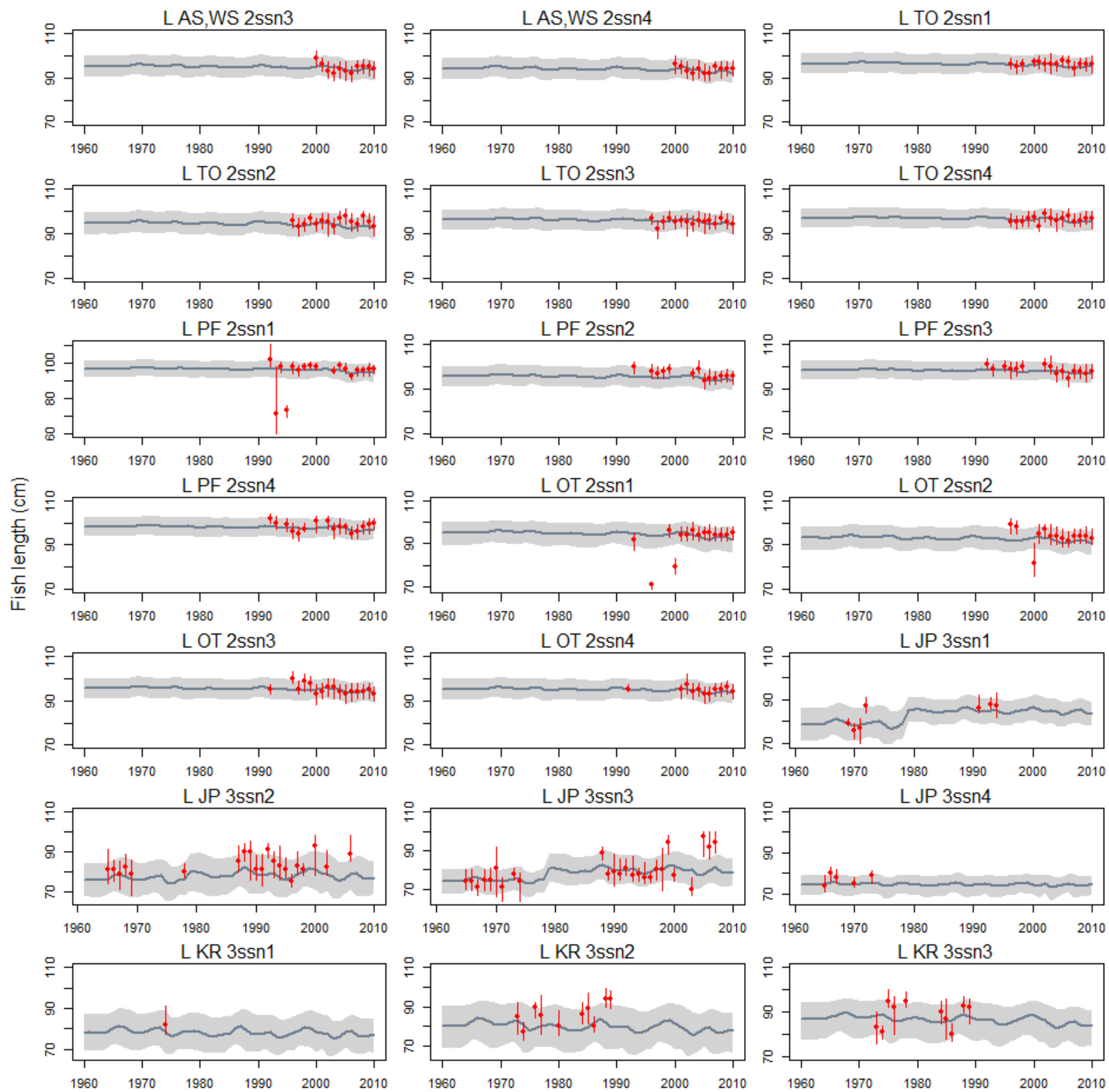


Figure 28c: A comparison of the observed (red points) and predicted (grey line) median fish length (FL, cm) of albacore tuna by fishery for the main fisheries with length data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated by year and only length samples with a minimum of 30 fish per year are plotted.

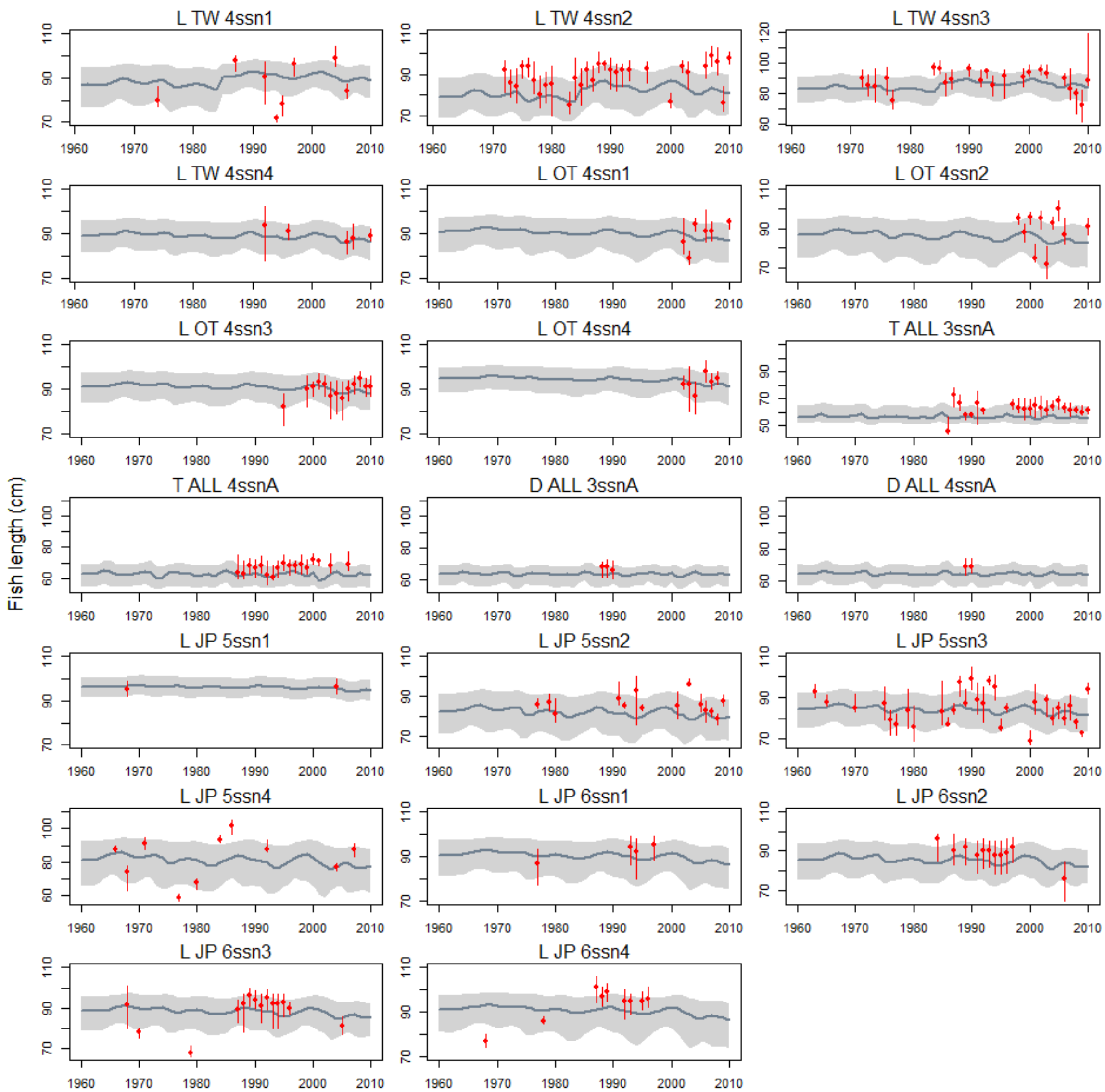


Figure 28 d: A comparison of the observed (red points) and predicted (grey line) median fish length (FL, cm) of albacore tuna by fishery for the main fisheries with length data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated by year and only length samples with a minimum of 30 fish per year are plotted**.**

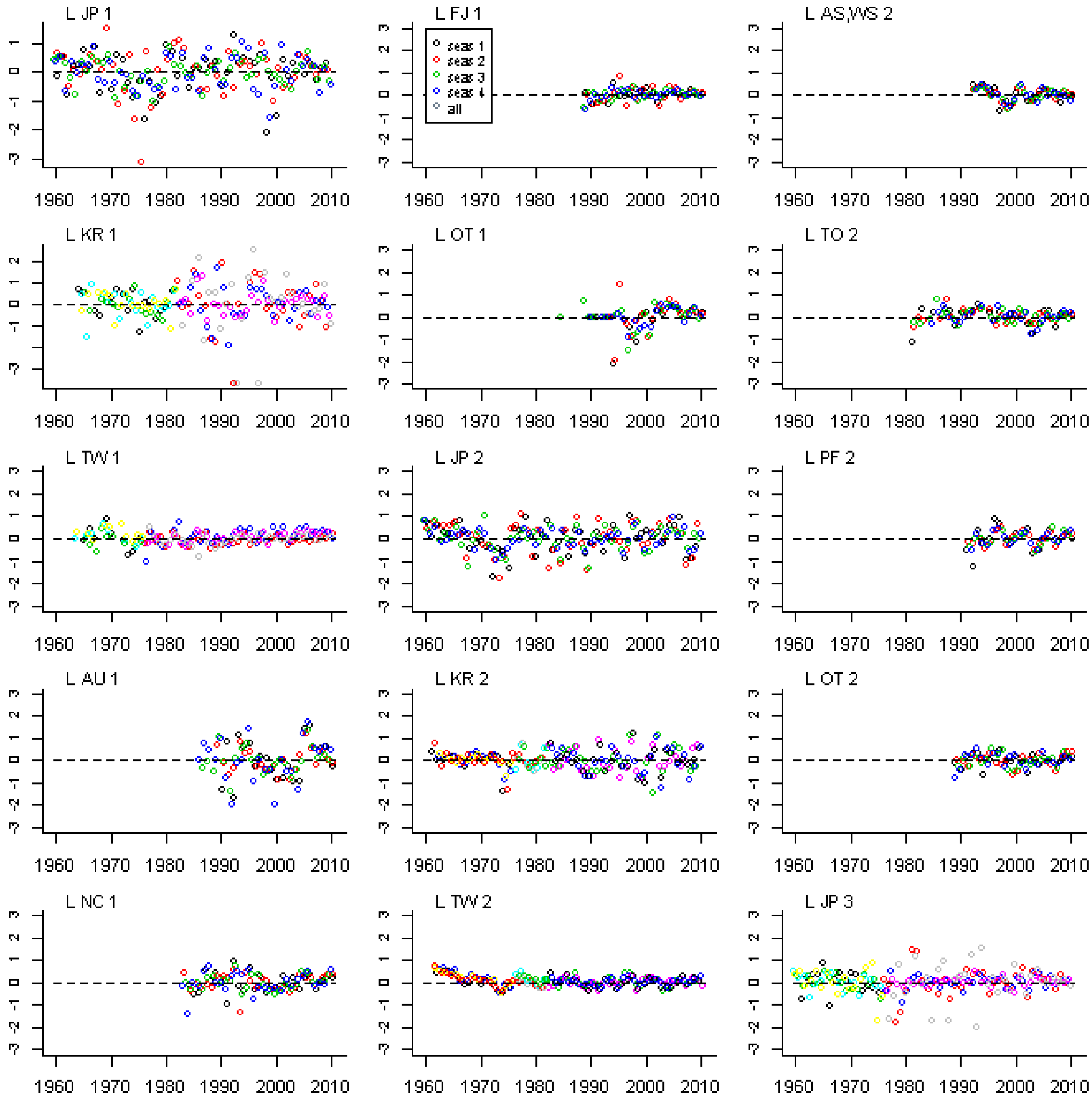


**Figure 29a: Quarterly effort deviates by fishery.**

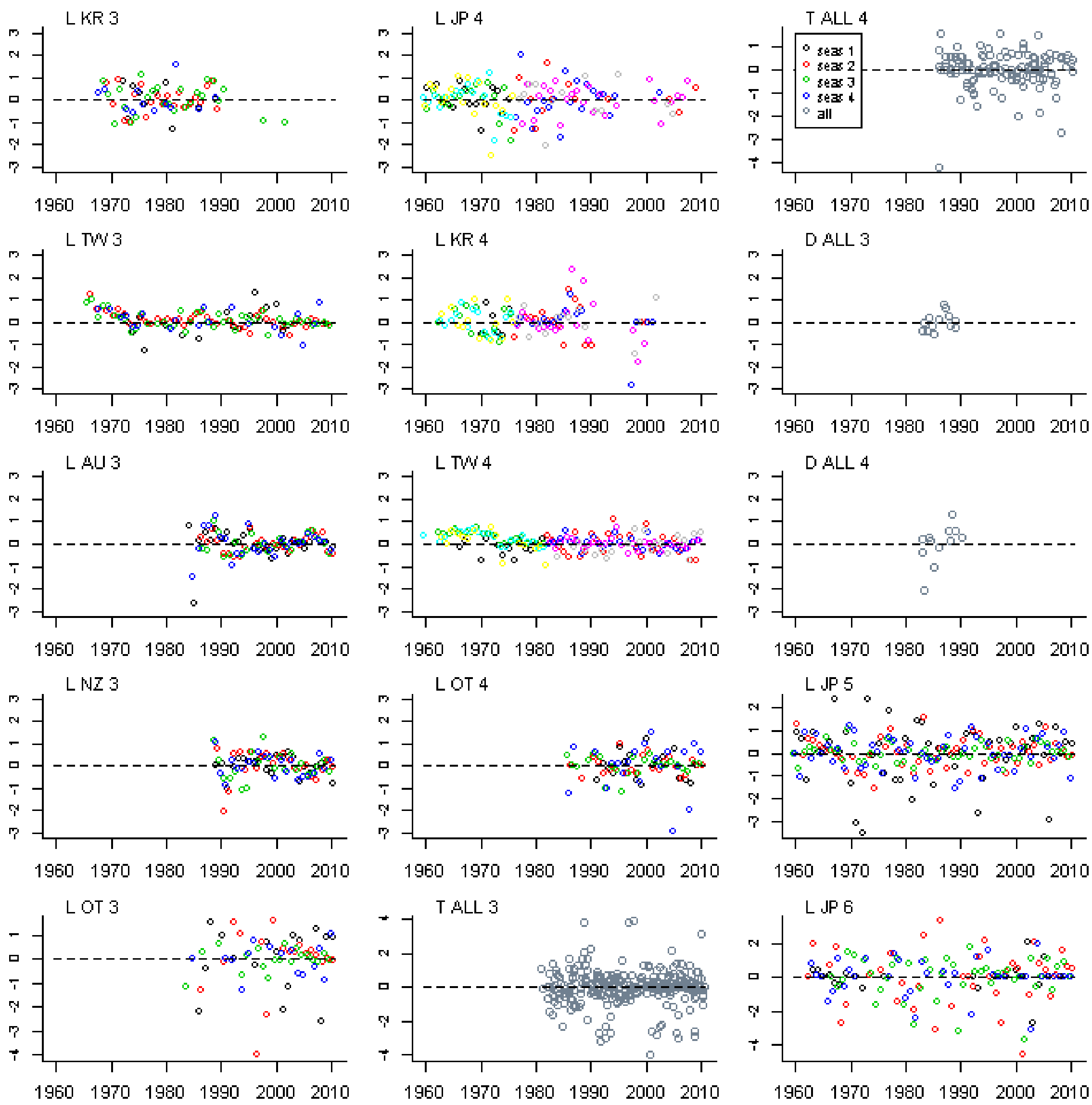


**Figure 29b: Quarterly effort deviates by fishery.**

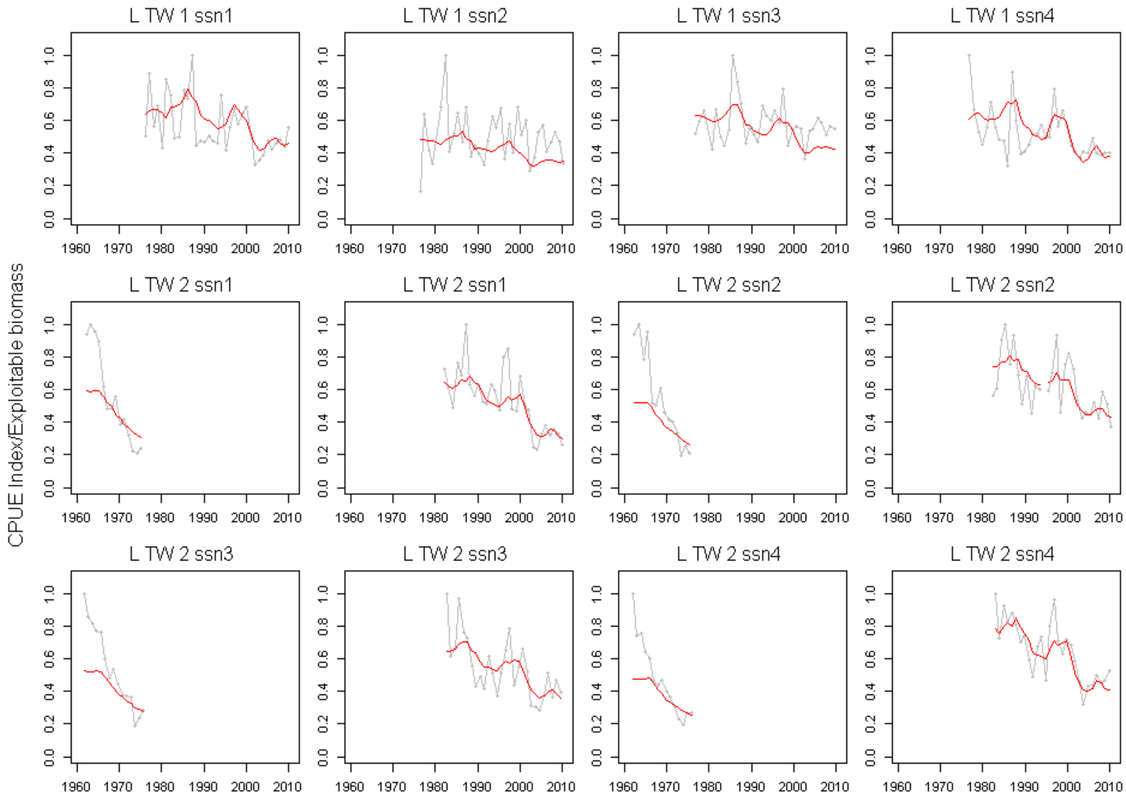


**Figure 30a: A comparison of the observed catch rate (number of fish) (grey points and line) and the predicted exploitable biomass from the quarterly observations of catch and effort from each of the standardised fisheries (red line).**

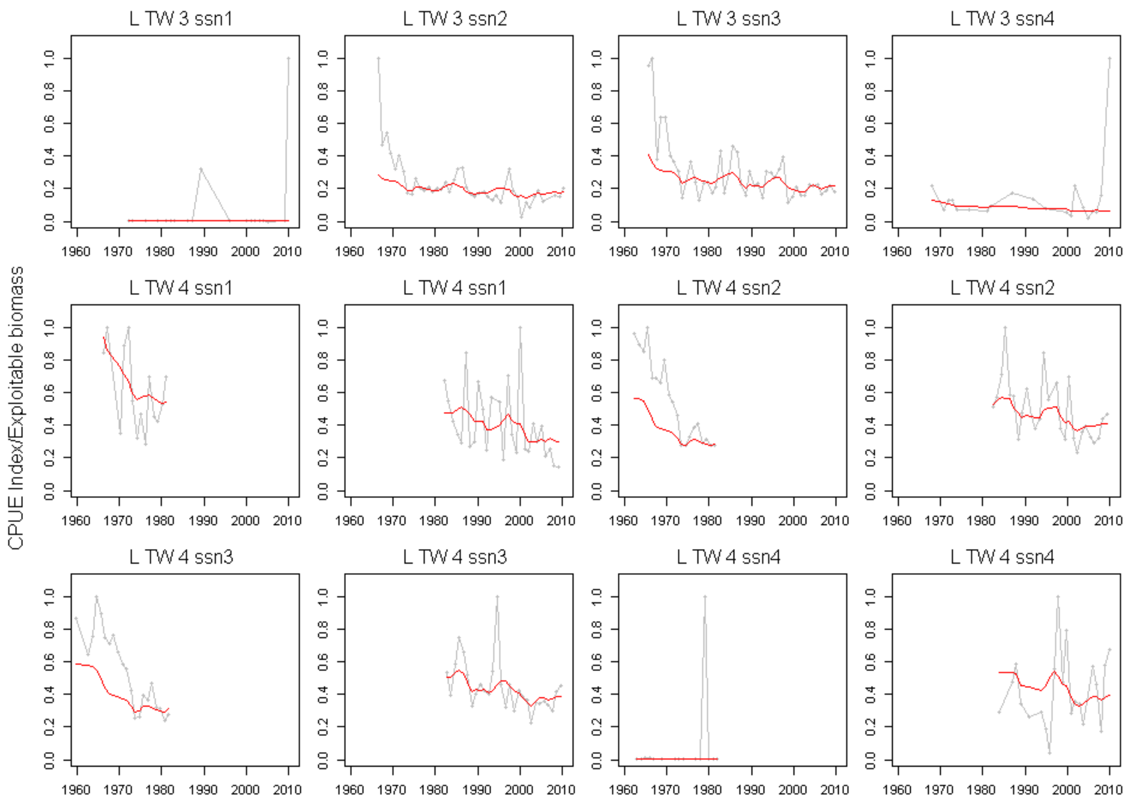


**Figure 30b: A comparison of the observed catch rate (number of fish) (grey points and line) and the predicted exploitable biomass from the quarterly observations of catch and effort from each of the standardised fisheries (red line).**

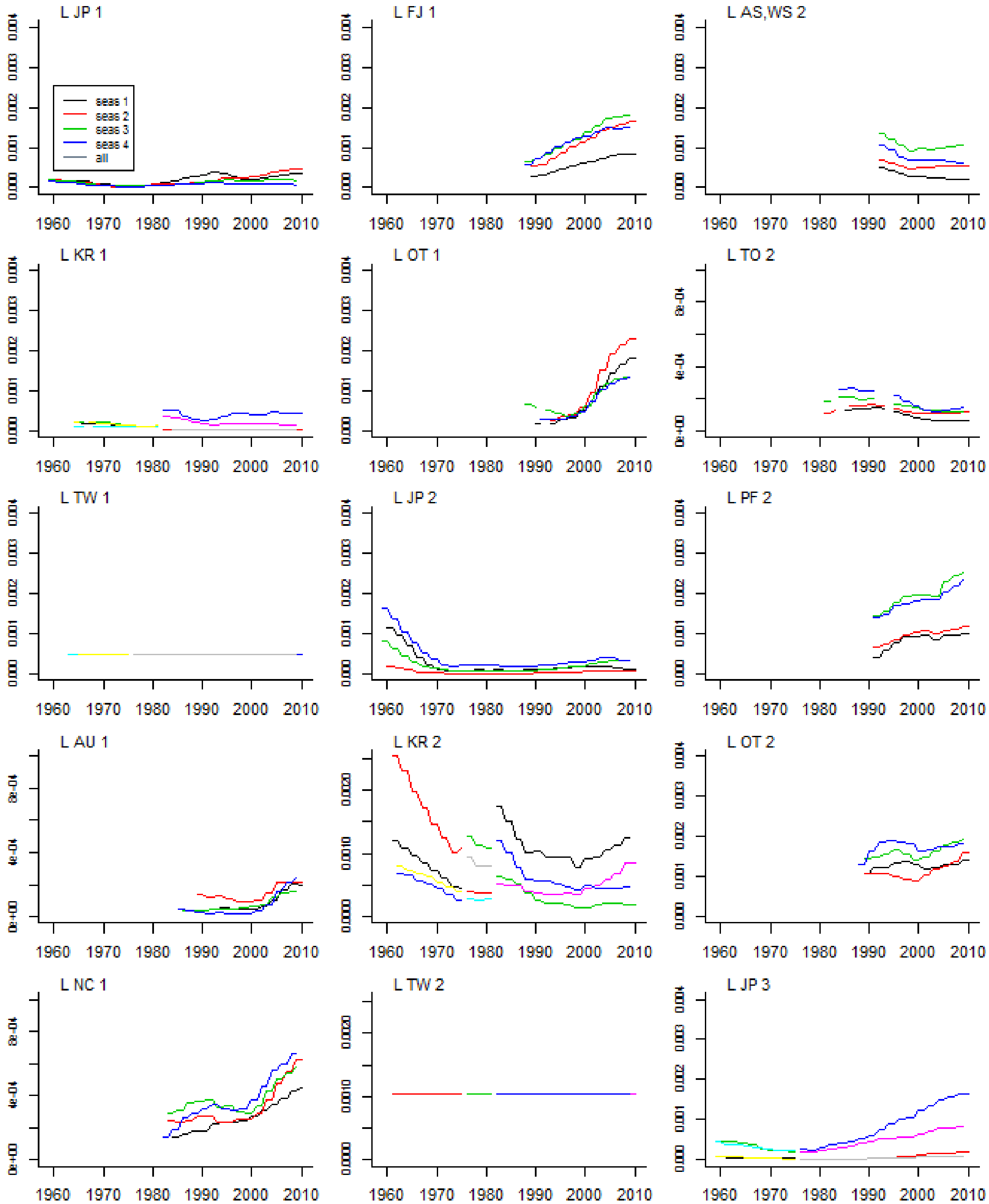


**Figure 31a: Annualised trends in catchability by fishery. The different coloured lines show the patterns by season.**

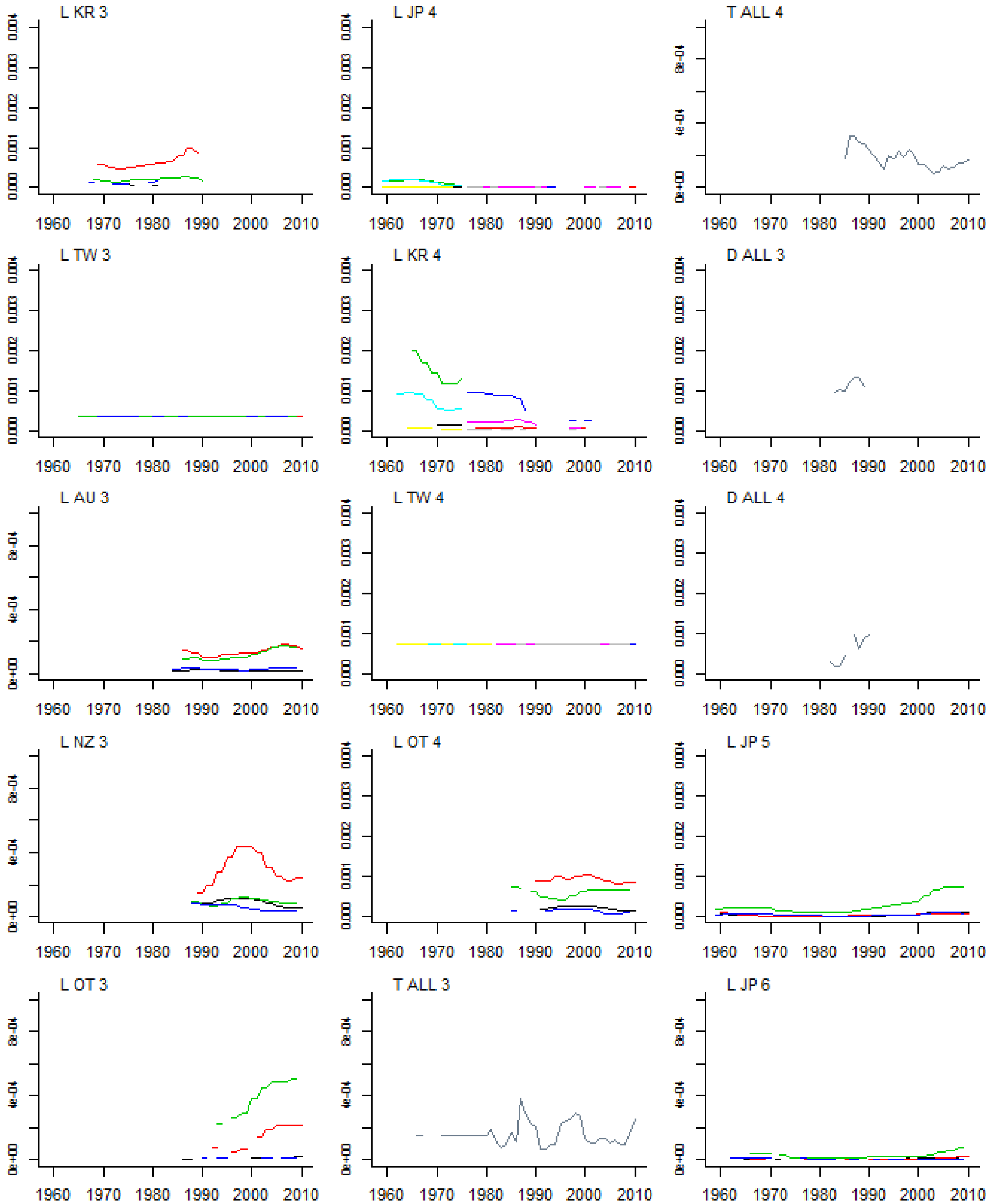


**Figure 31b: Annualised trends in catchability by fishery. The different coloured lines show the patterns by season.**

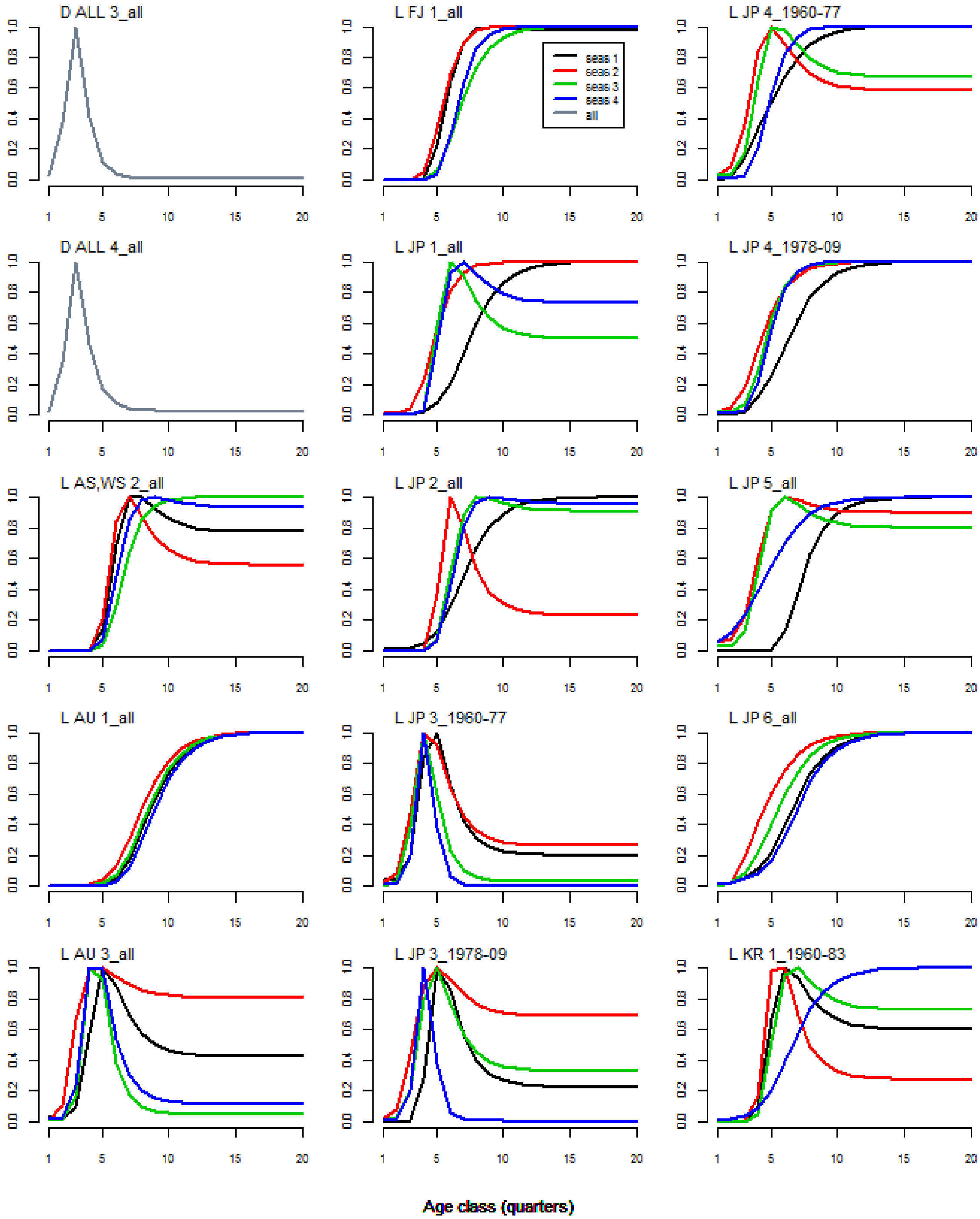


**Figure 32a: Selectivity at age (years) by fishery. The different coloured lines show the patterns by season.**

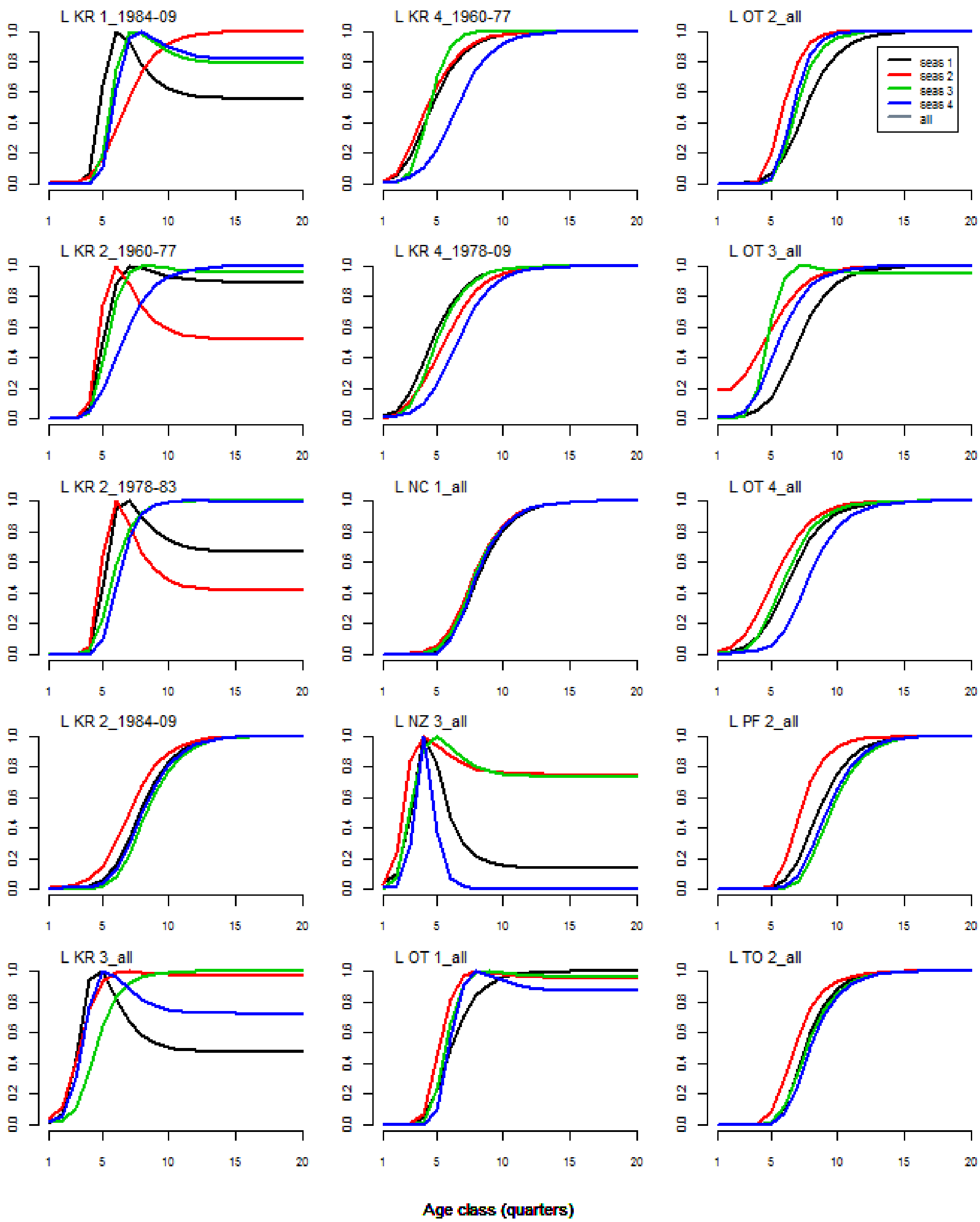


**Figure 32b: Selectivity at age (years) by fishery. The different coloured lines show the patterns by season.**

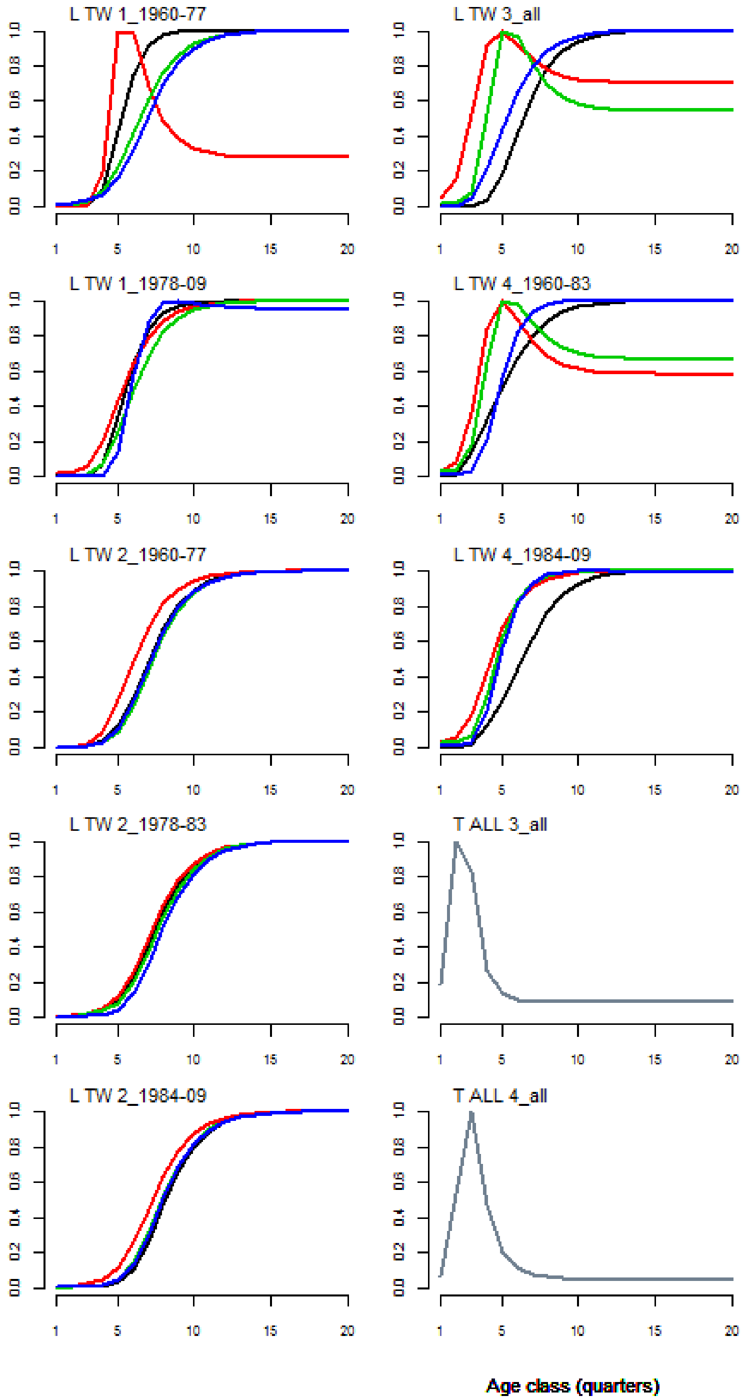


**Figure 32**c: **Selectivity at age (years) by fishery. The different coloured lines show the patterns by season.**

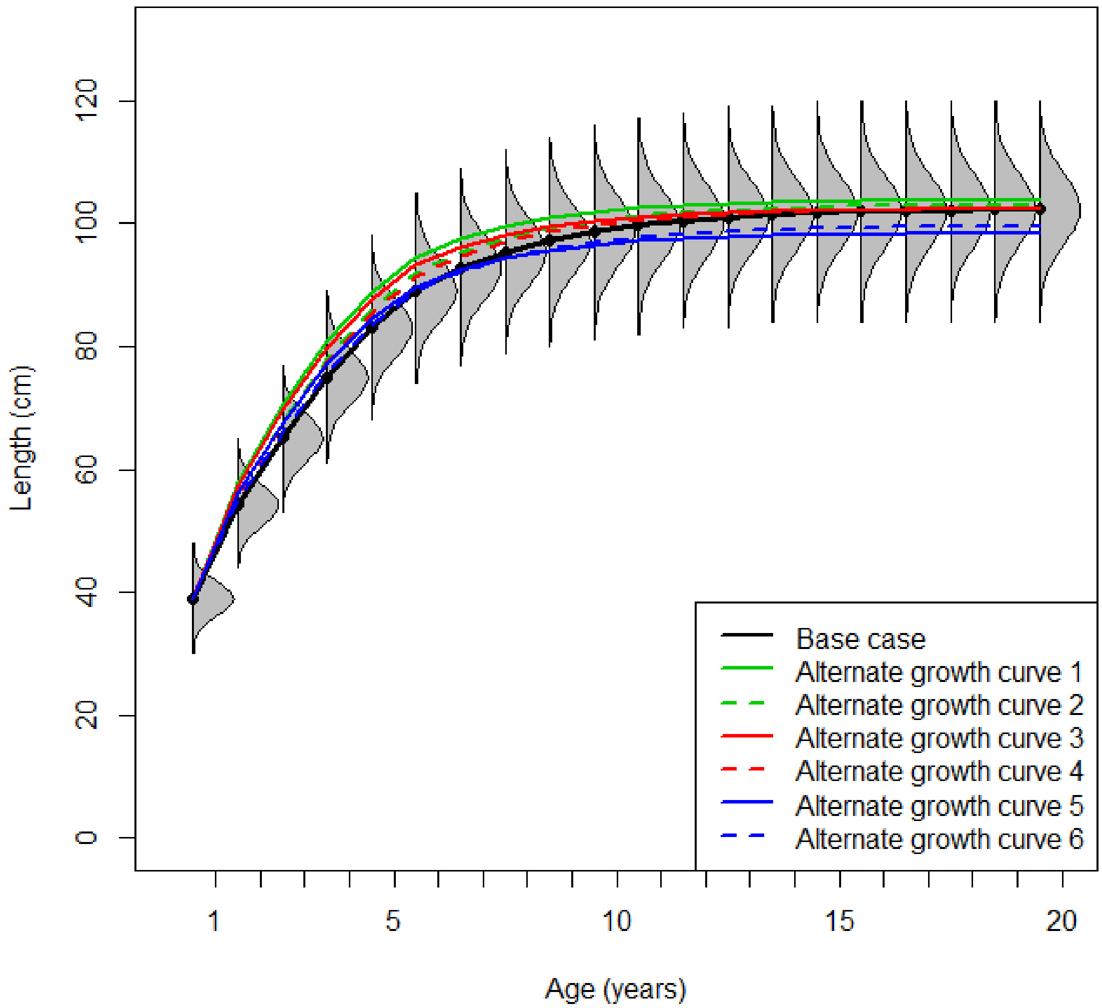


**Figure 33: Estimated length (fork length) at age (years) (solid line) and the 95% confidence interval. The coloured lines represent six alternative growth curves run as sensitivity analyses.**

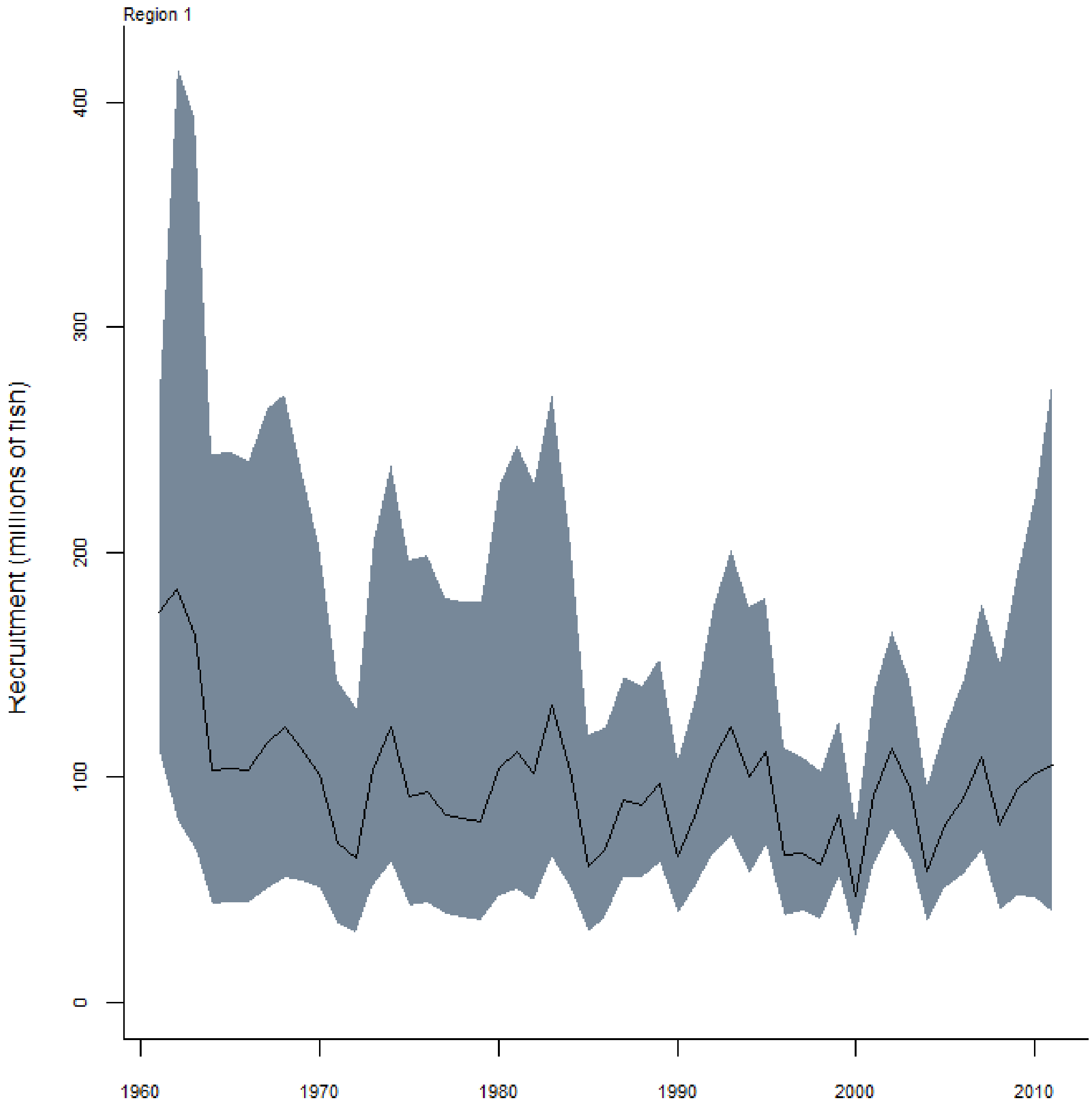


**Figure 34: Annual recruitment (number of fish) estimates. The grey area represents parameter uncertainty estimated from the Hessian matrix.**

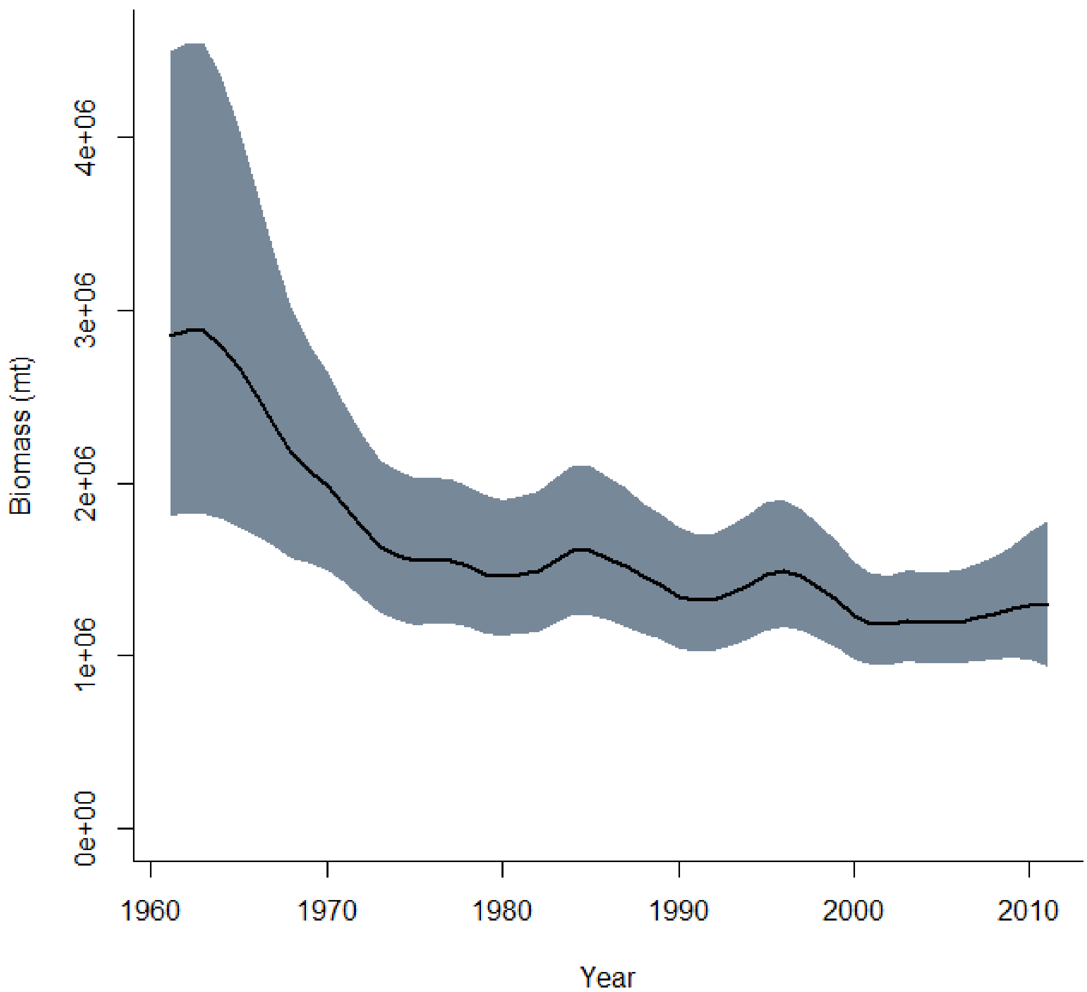


**Figure 35: Annual estimates of total biomass (thousands of metric tonnes). The grey area represents parameter uncertainty estimated from the Hessian matrix.**

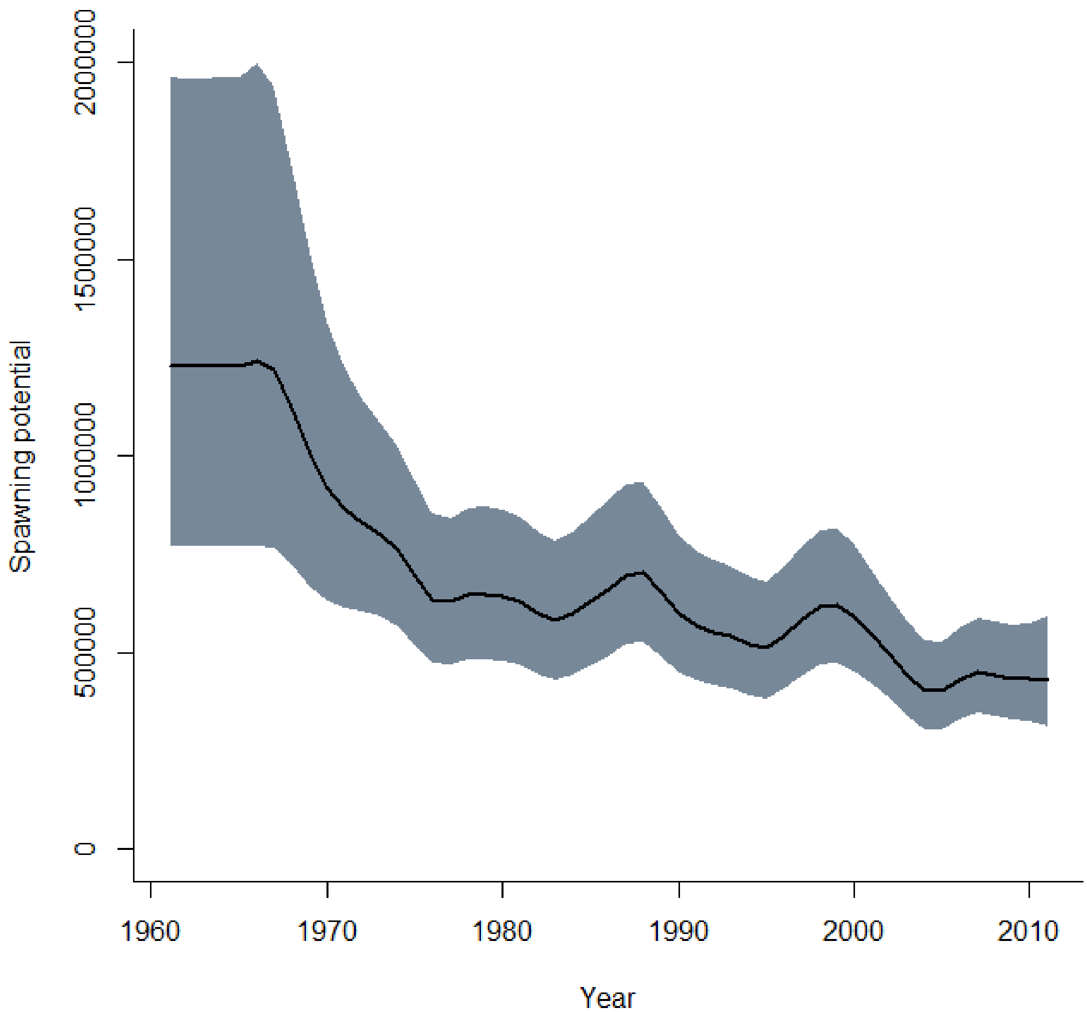


Figure 36: **Annual estimates of spawning potential, also referred to as adult biomass. The grey area represents parameter uncertainty estimated from the Hessian matrix.**

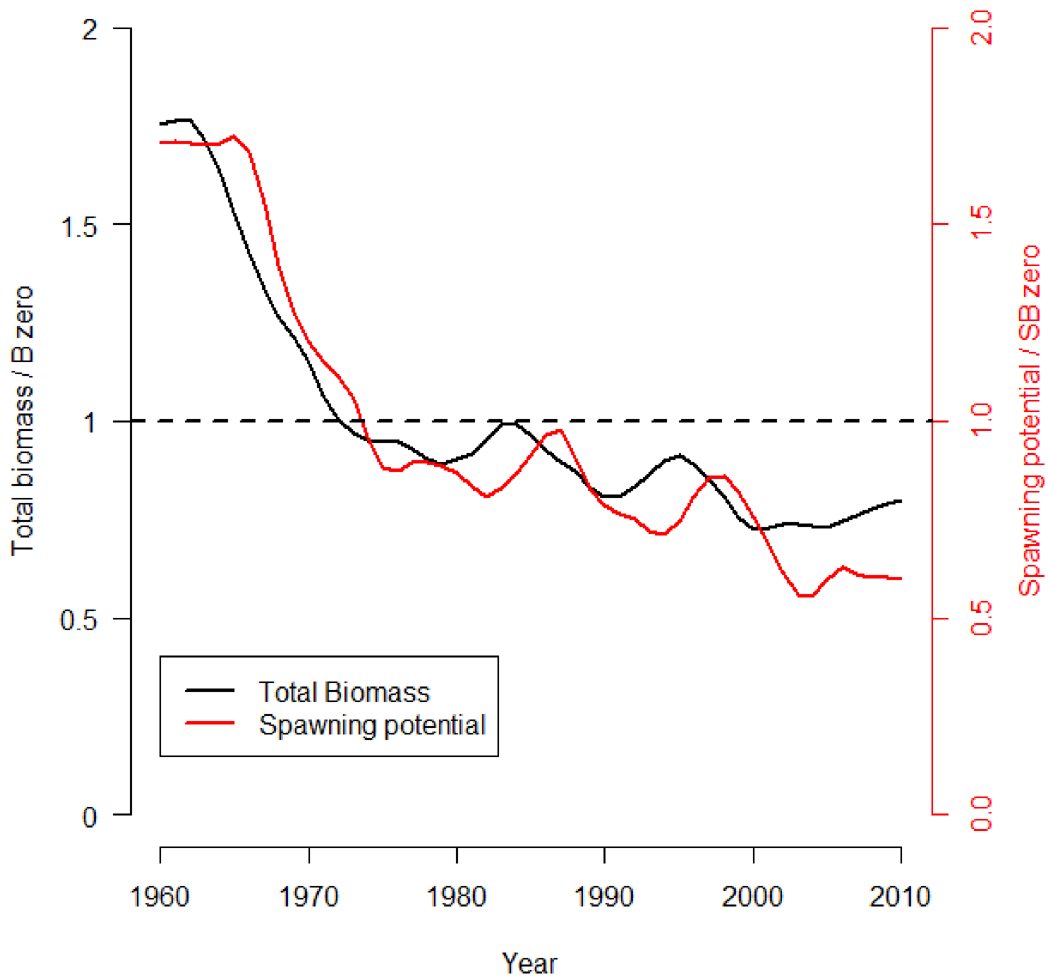


**Figure 37: Time series of the ratios $B$ / $B_0$ and $SB$ / $SB_0$. Initial biomasses are estimated to be well above equilibrium unfished levels (represented by $B_0$ and $SB_0$).**

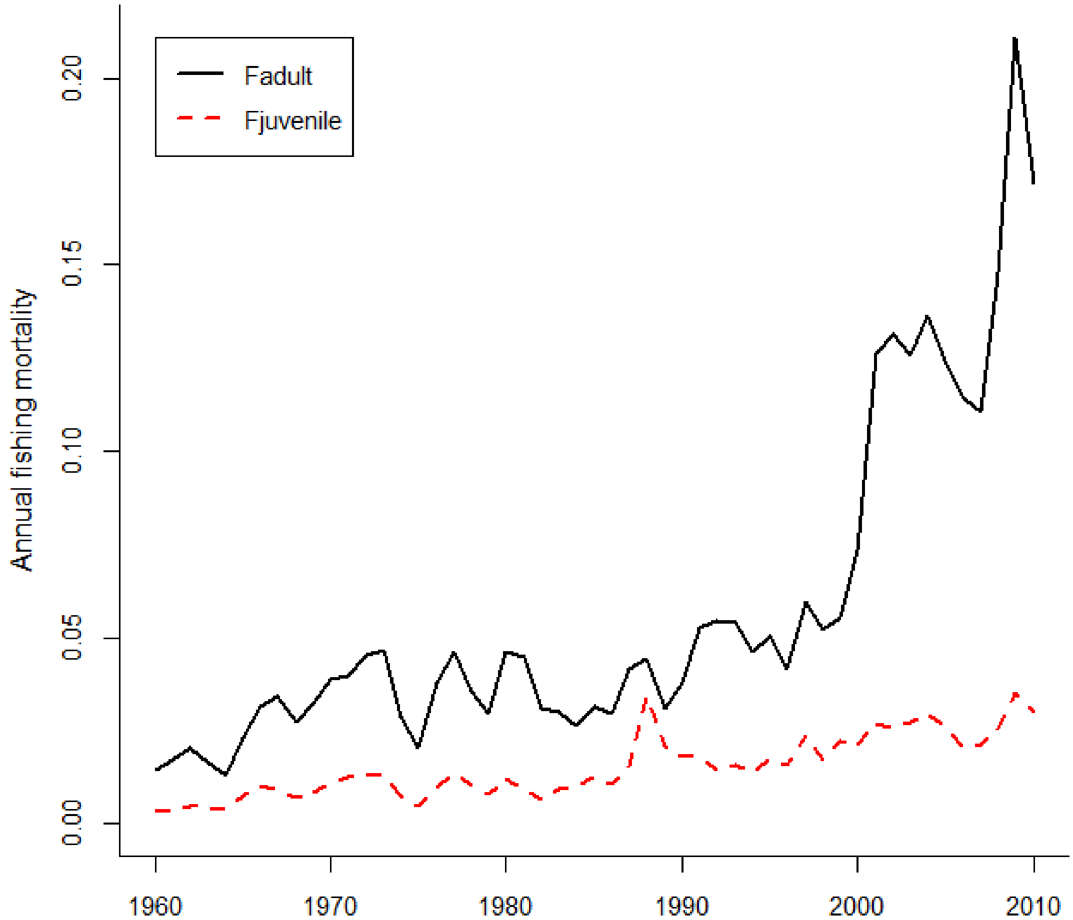


**Figure 38: Annual estimates of fishing mortality for juvenile and adult South Pacific albacore.**

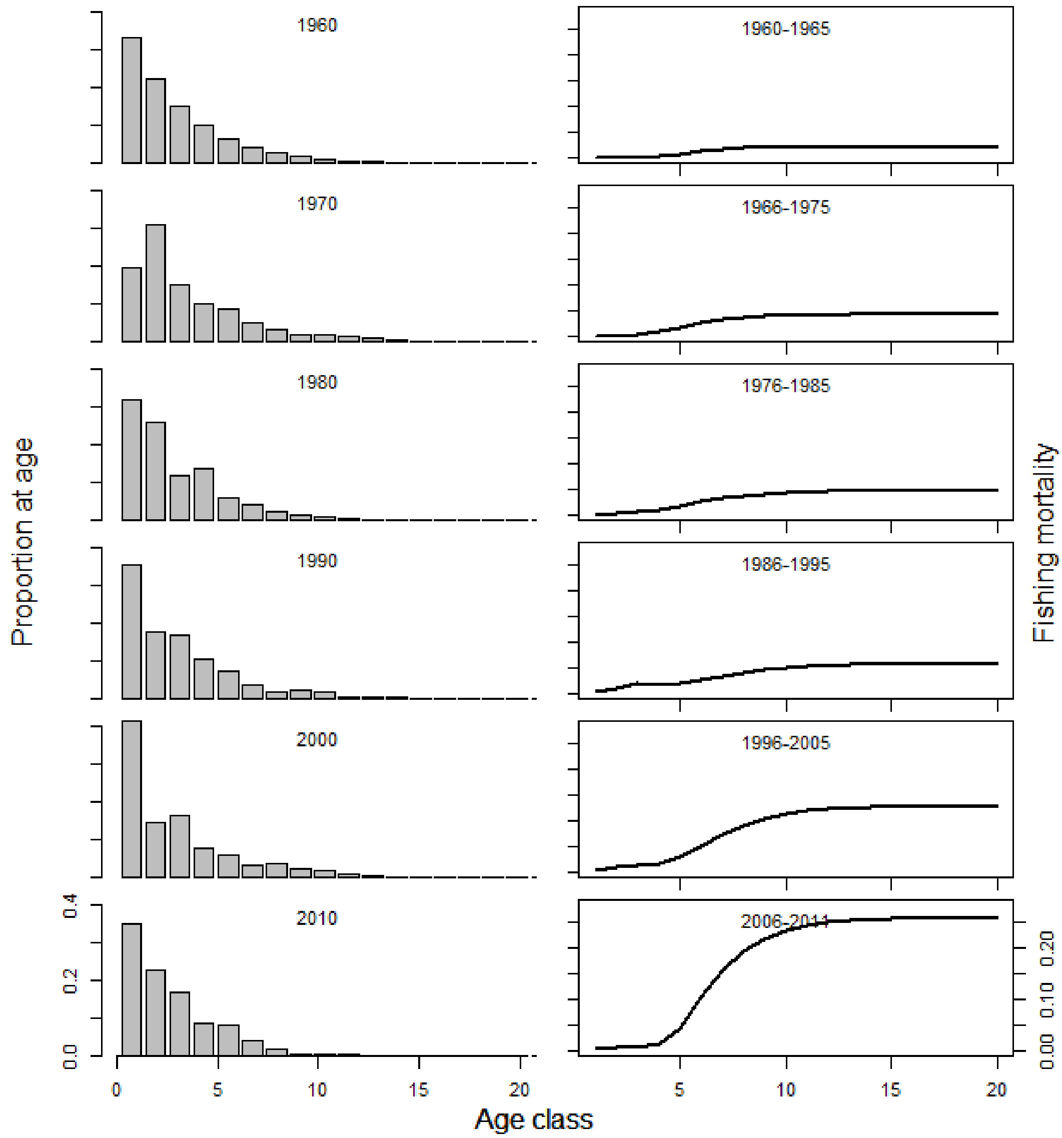


**Figure 39: Estimated proportion at age (left) and mortality at age (right) by year at decadal intervals.**

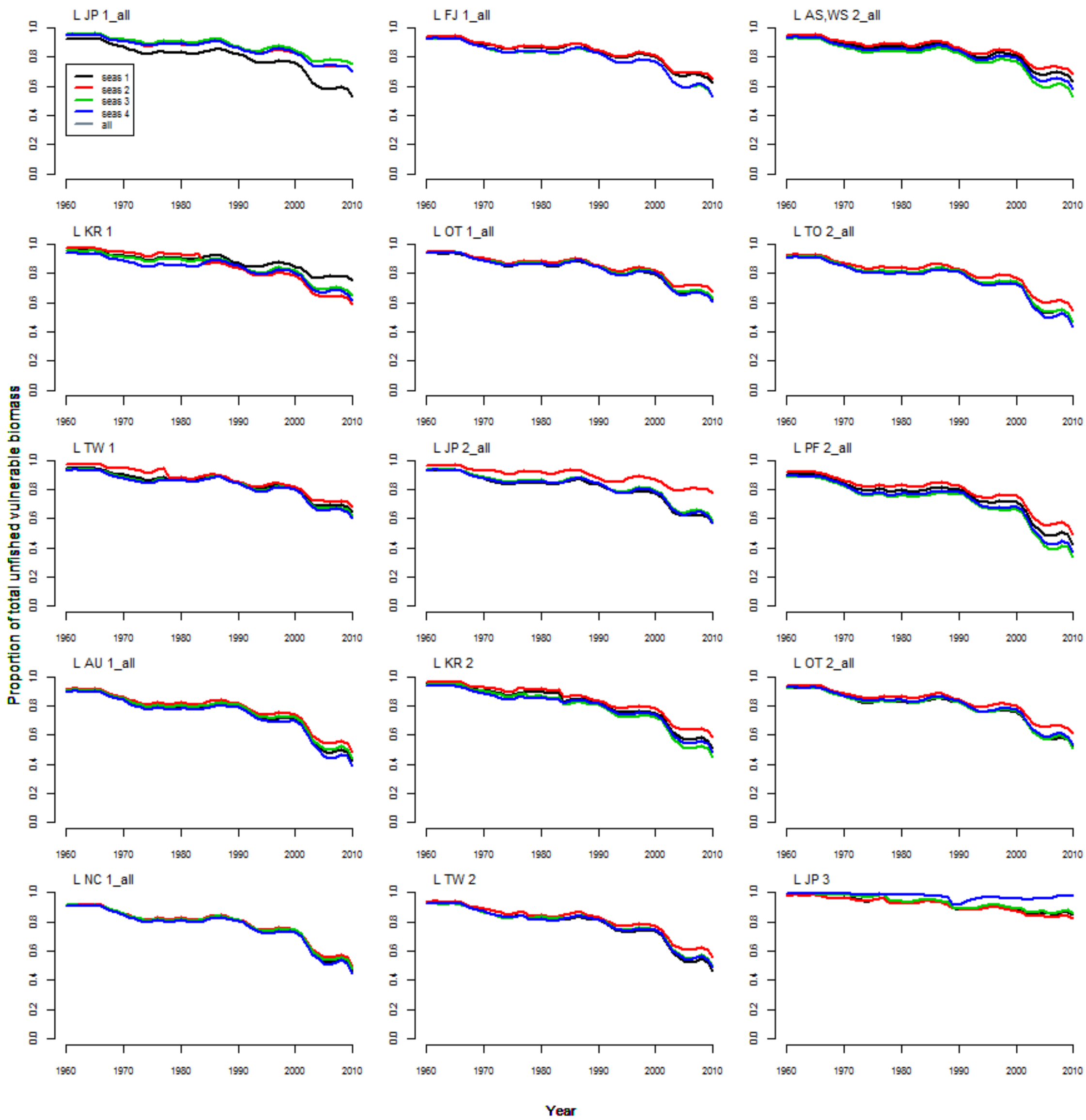


**Figure 40a: The ratio between the level of exploitable biomass for individual fisheries and the level of exploitable biomass predicted in the absence of fishing.**

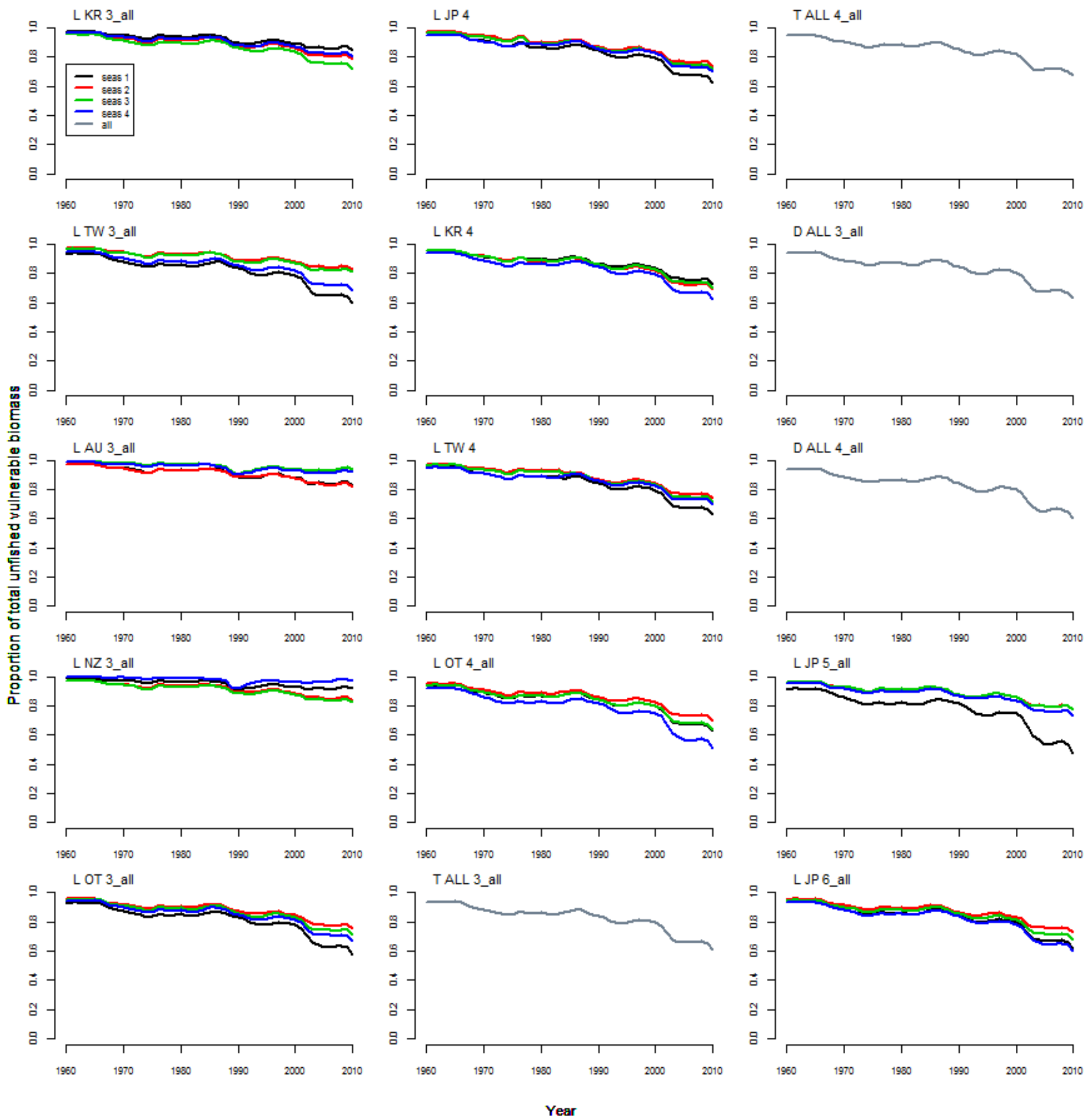


**Figure 40b: The ratio between the level of exploitable biomass for individual fisheries and the level of exploitable biomass predicted in the absence of fishing.**

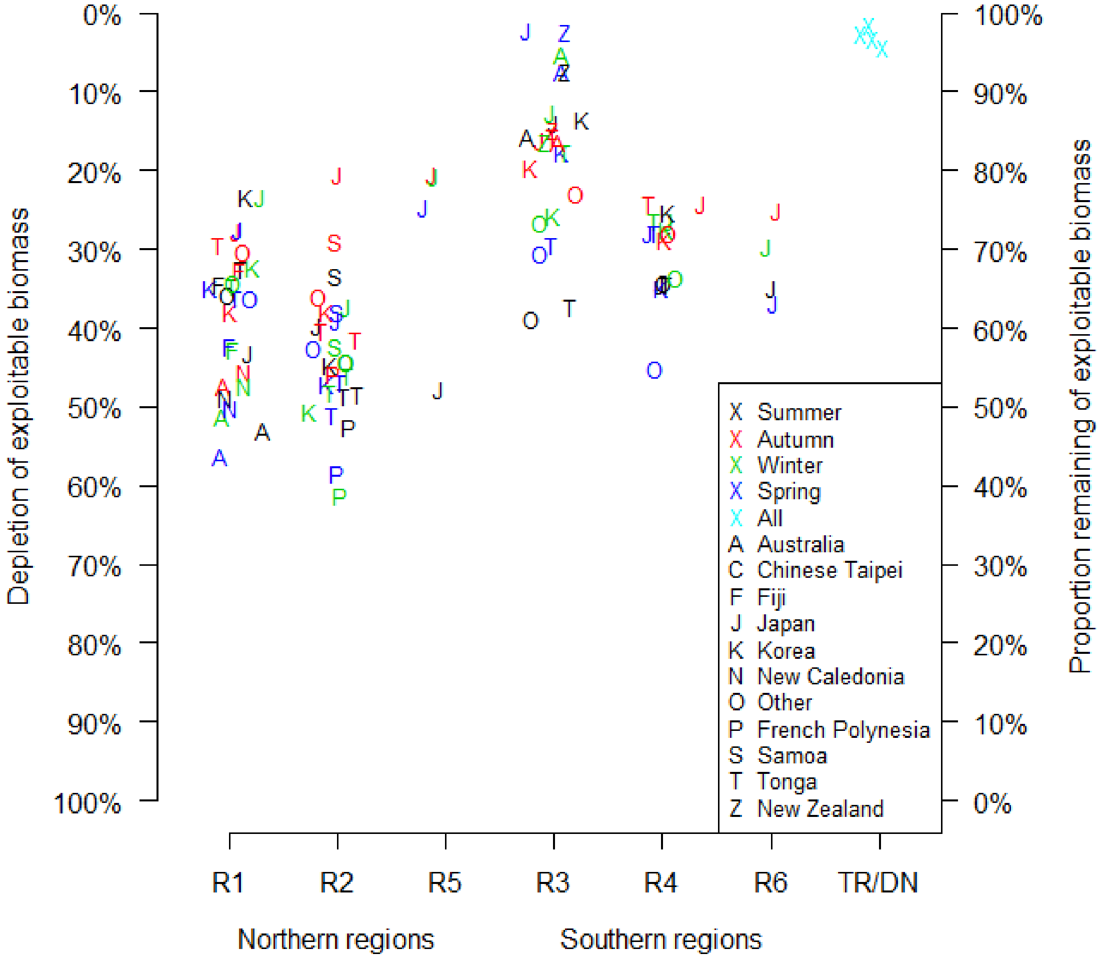


**Figure 41: Average depletion (due to all fishing) of exploitable biomass by fishery for the period 2007–2010, by fishery. Fisheries are coloured by season, and labelled according to fishing nation. The four light blue crosses represent the troll and driftnet fisheries.**

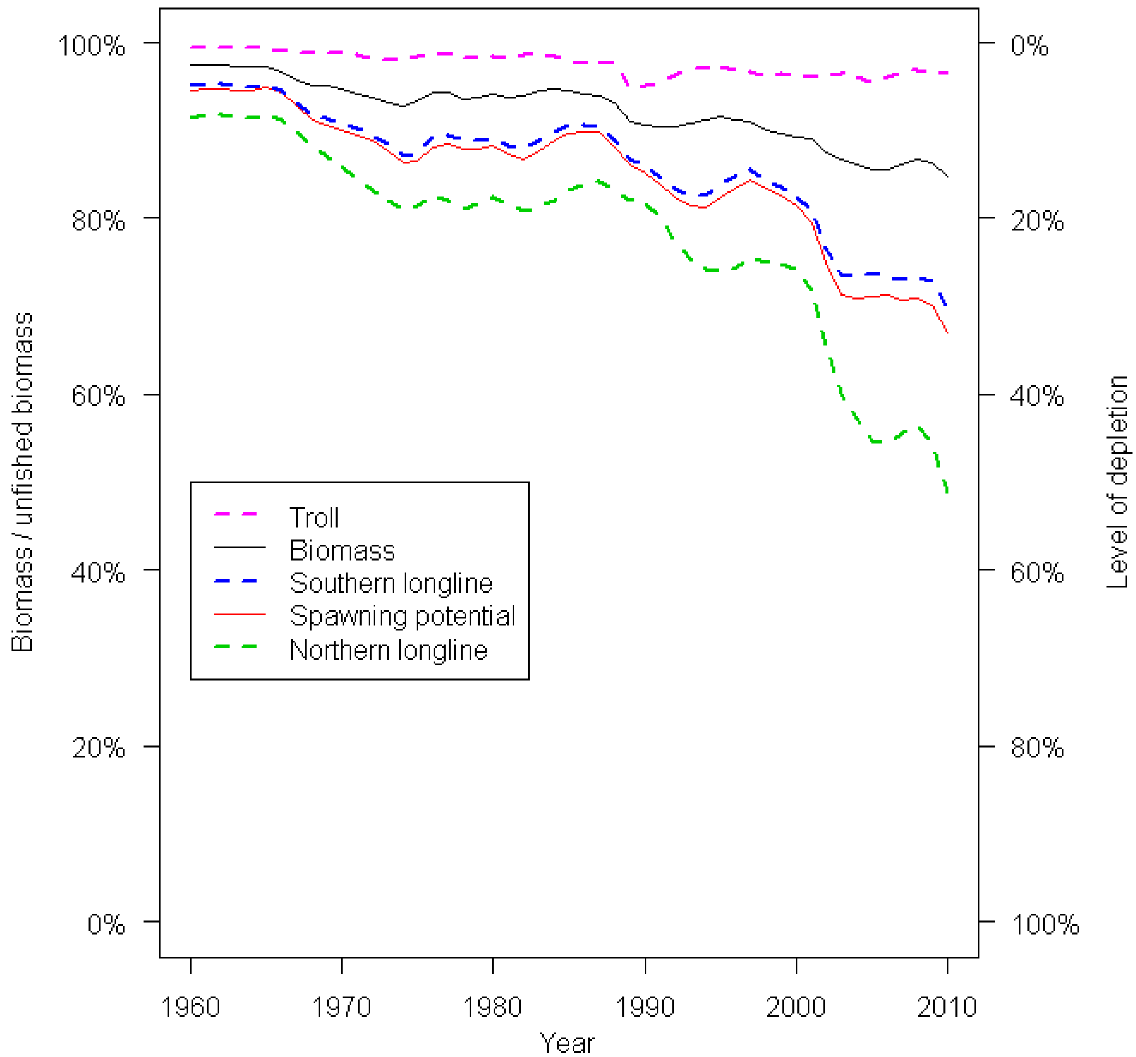


**Figure 42: Decline in biomass due to the impact of fishing mortality, for exploitable biomass in the troll, southern longline, and northern longline fisheries, for total biomass and for spawning potential.**

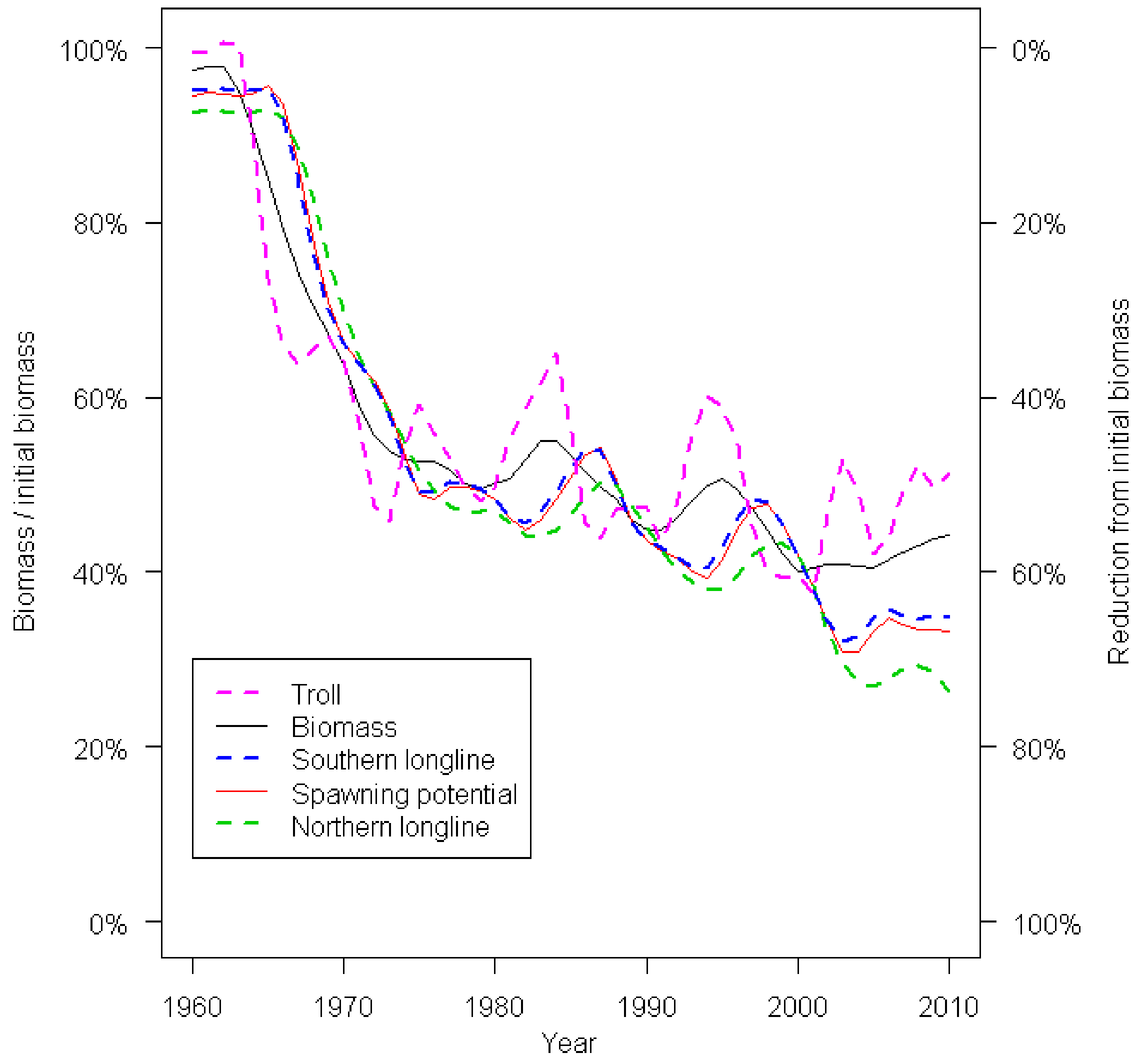


**Figure 43: Decline in biomass relative to initial biomass $B_0$, for exploitable biomass in the troll, southern longline, and northern longline fisheries, for total biomass, and for spawning potential.**

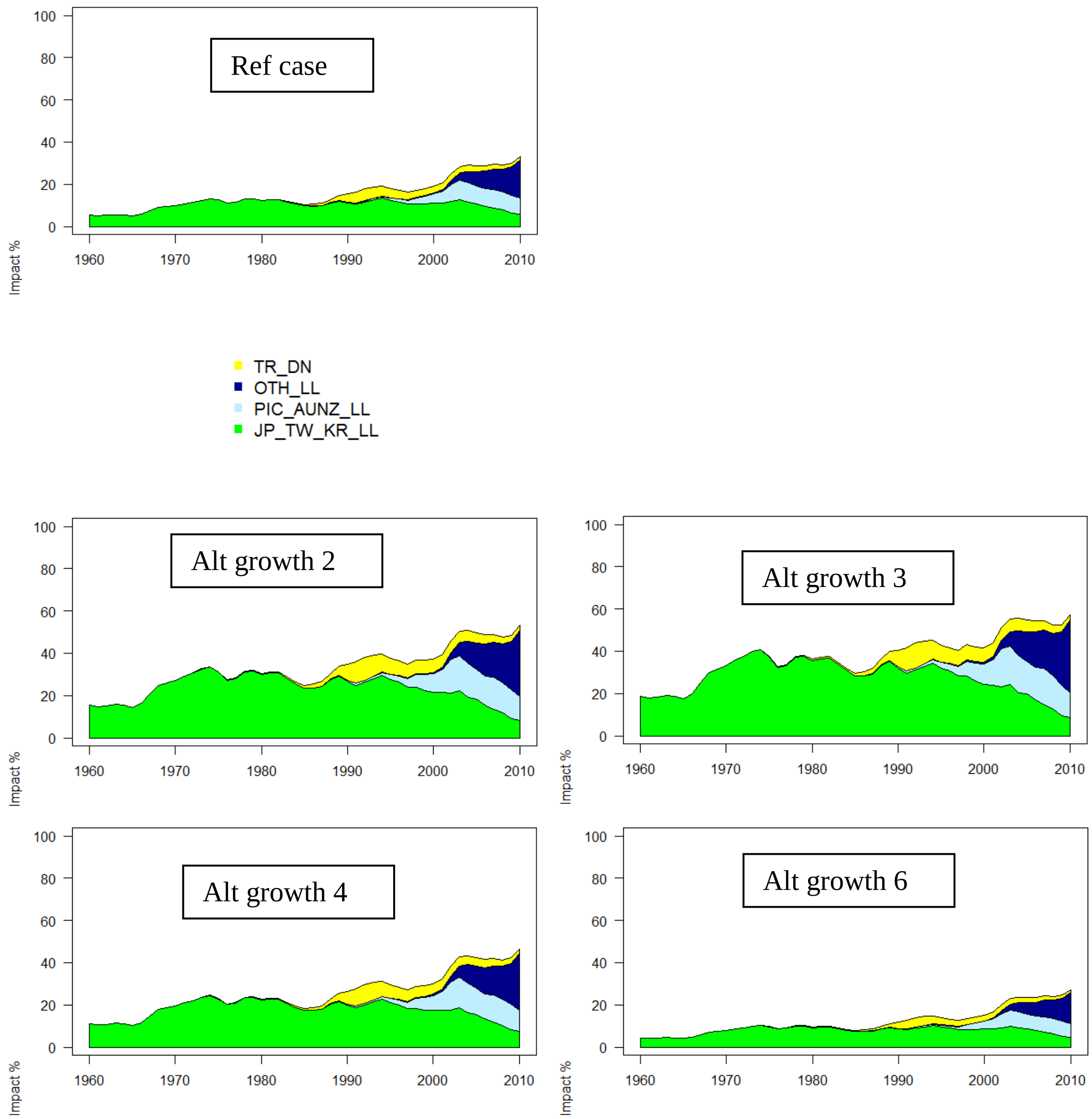


**Figure 44:** Estimates of reduction in spawning potential due to fishing (fishery impact = $1 - SB_t/SB_{t_{F=0}}$ ) attributed to various fishery groups (TR_DN = Troll and driftnet fisheries; OTH_LL = 'Other' Longline fisheries; PIC_AUNZ_LL = Pacific Island and Australia and New Zealand longline fisheries; JP_TW_KR_LL = Japanese, Korean and Chinese Taipei distant water longline fisheries). Results are shown for the reference case and for the various sensitivity analyses included in the grid.

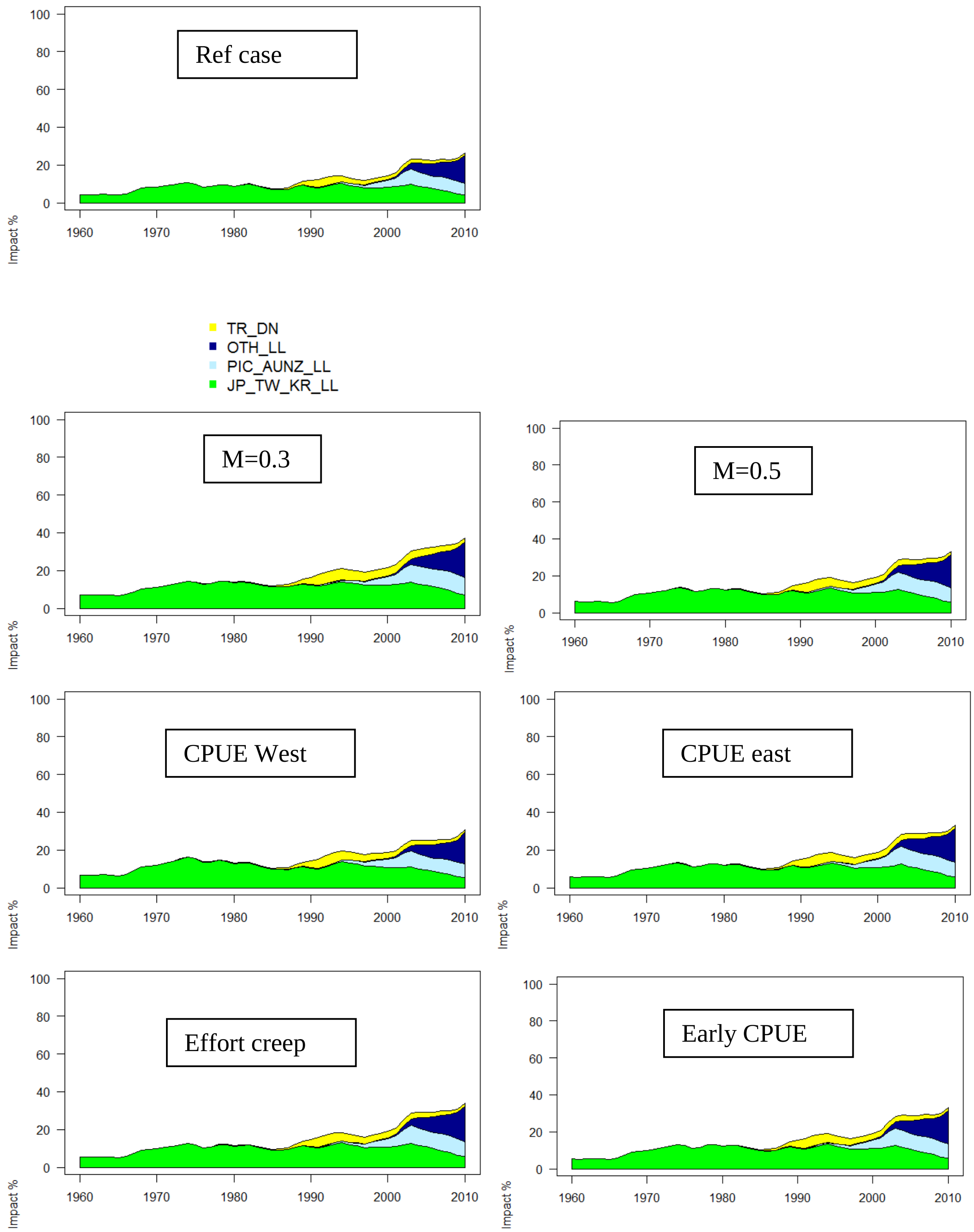


**Figure 44**b: Estimates of reduction in spawning potential due to fishing (fishery impact = $1 - SB_t/SB_{t_{F=0}}$ ) attributed to various fishery groups (TR_DN = Troll and driftnet fisheries; OTH_LL = ‘Other’ Longline fisheries; PIC_AUNZ_LL = Pacific Island and Australia and New Zealand longline fisheries; JP_TW_KR_LL = Japanese, Korean and Chinese Taipei distant water longline fisheries). Results are shown for the reference case and for the various sensitivity analyses included in the grid.

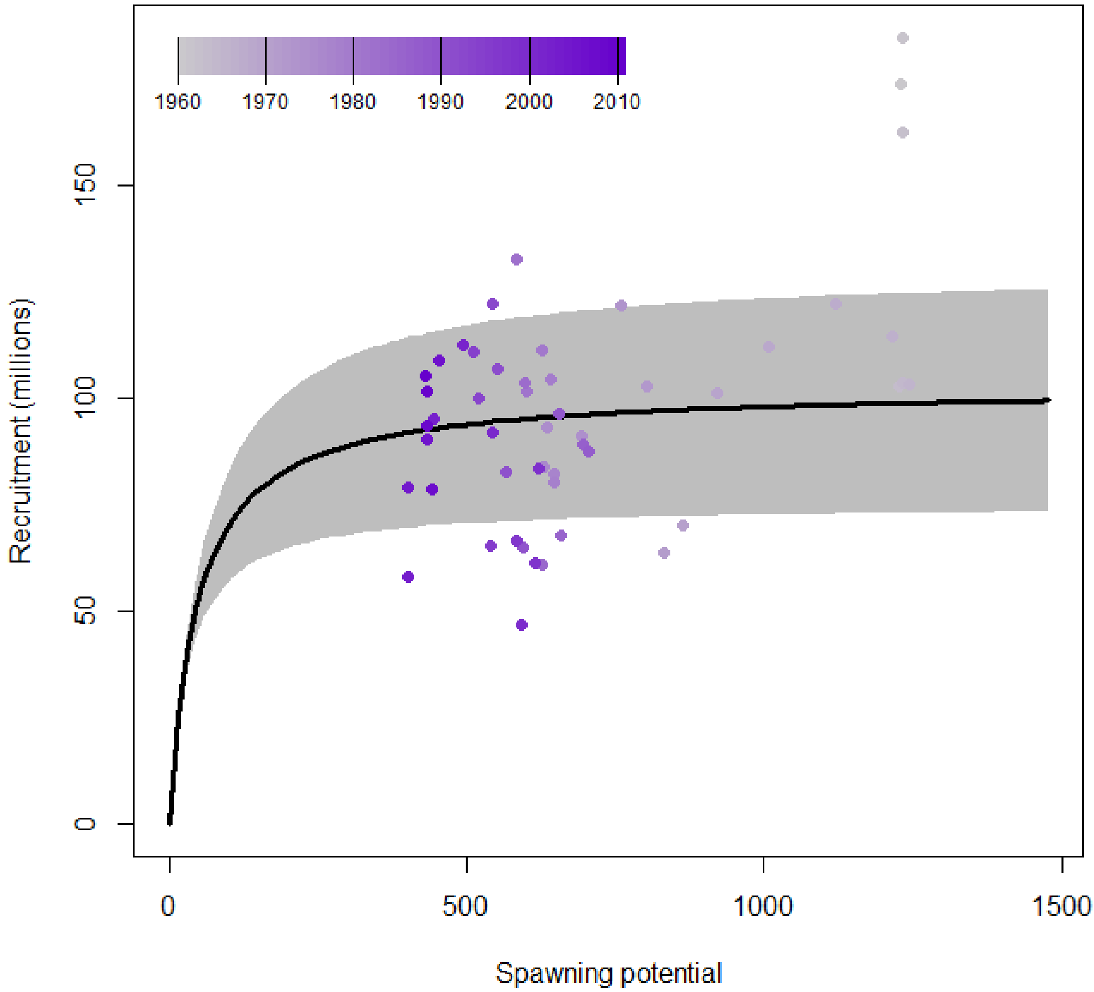


**Figure 45. Spawning potential–recruitment estimates and the fitted Beverton-Holt stock-recruitment relationship (SRR). The grey area represents parameter uncertainty estimated from the Hessian matrix.**

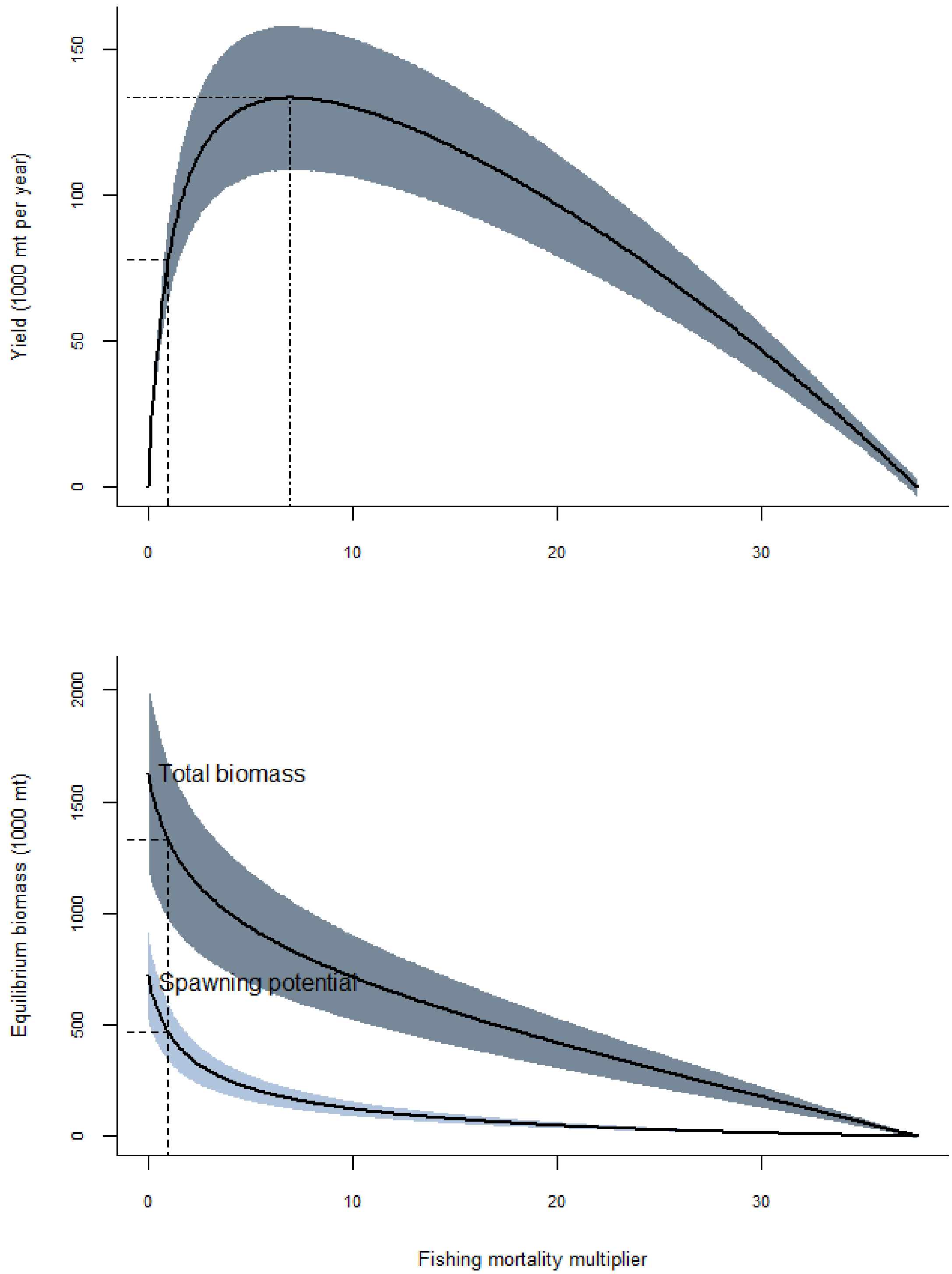


**Figure 46a: Reference case estimates of yield, equilibrium biomass and equilibrium spawning potential as a function of fishing mortality multiplier. In the top figure, dotted lines indicate equilibrium yield at the current fishing mortality, and maximum sustainable yield. In the lower figure, dotted lines represent equilibrium values of spawning potential and total biomass at current fishing mortality. The grey area represents uncertainty in the yield resulting from parameter uncertainty.**

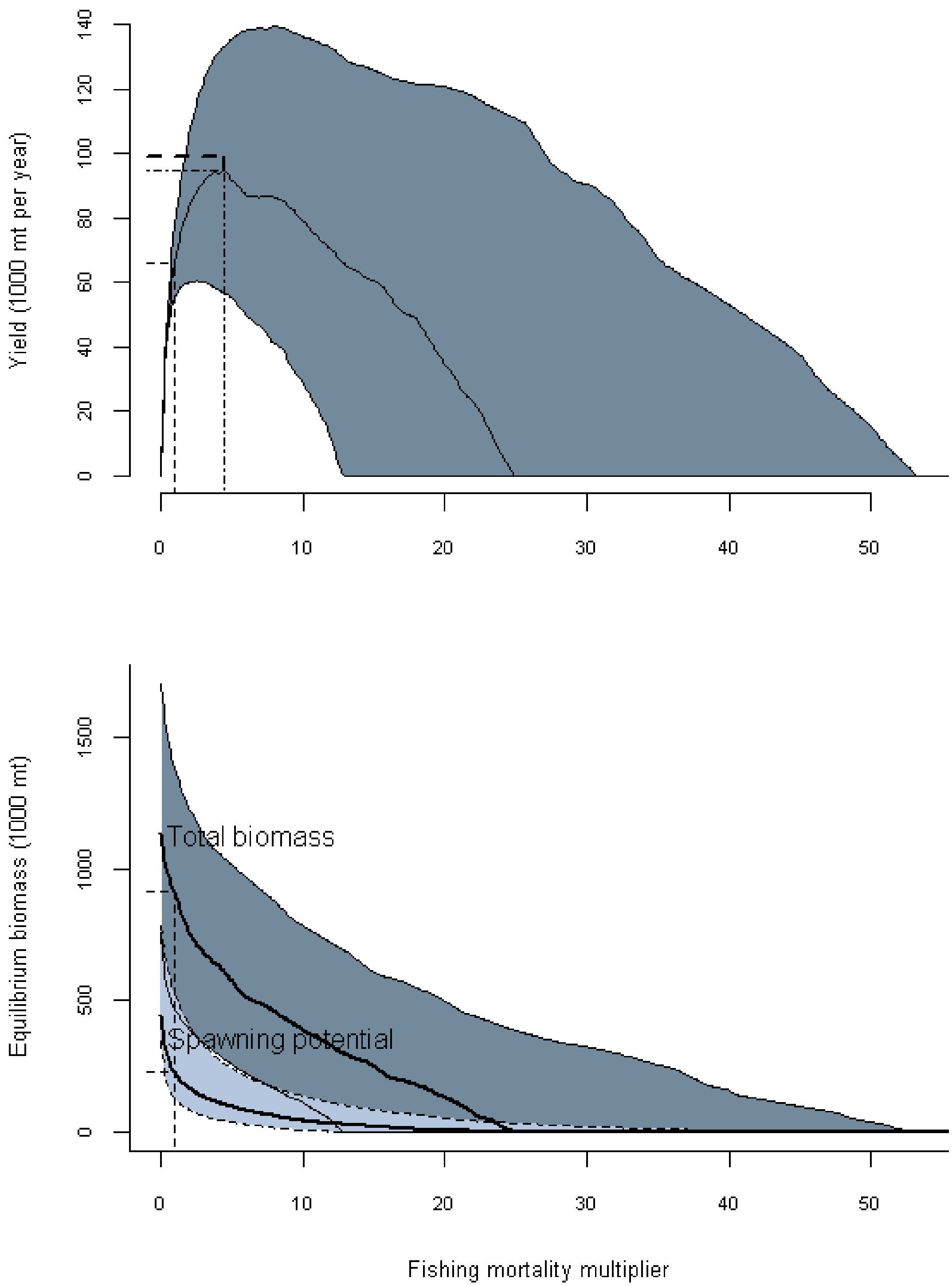


**Figure 46b: Structural sensitivity analyses of yield, equilibrium biomass and equilibrium spawning potential as a function of fishing mortality multiplier. In the top figure, dotted lines indicate median estimates of equilibrium yield at the current fishing mortality, and at the F that gives maximum sustainable yield. Note that the median of maximum yields differs slightly from maximum of median yields – both are indicated. In the lower figure, dotted lines represent median estimates of equilibrium values of spawning potential and total biomass at current fishing mortality. The unbroken lines track the medians, and the grey area represents uncertainty resulting from structural uncertainty.**

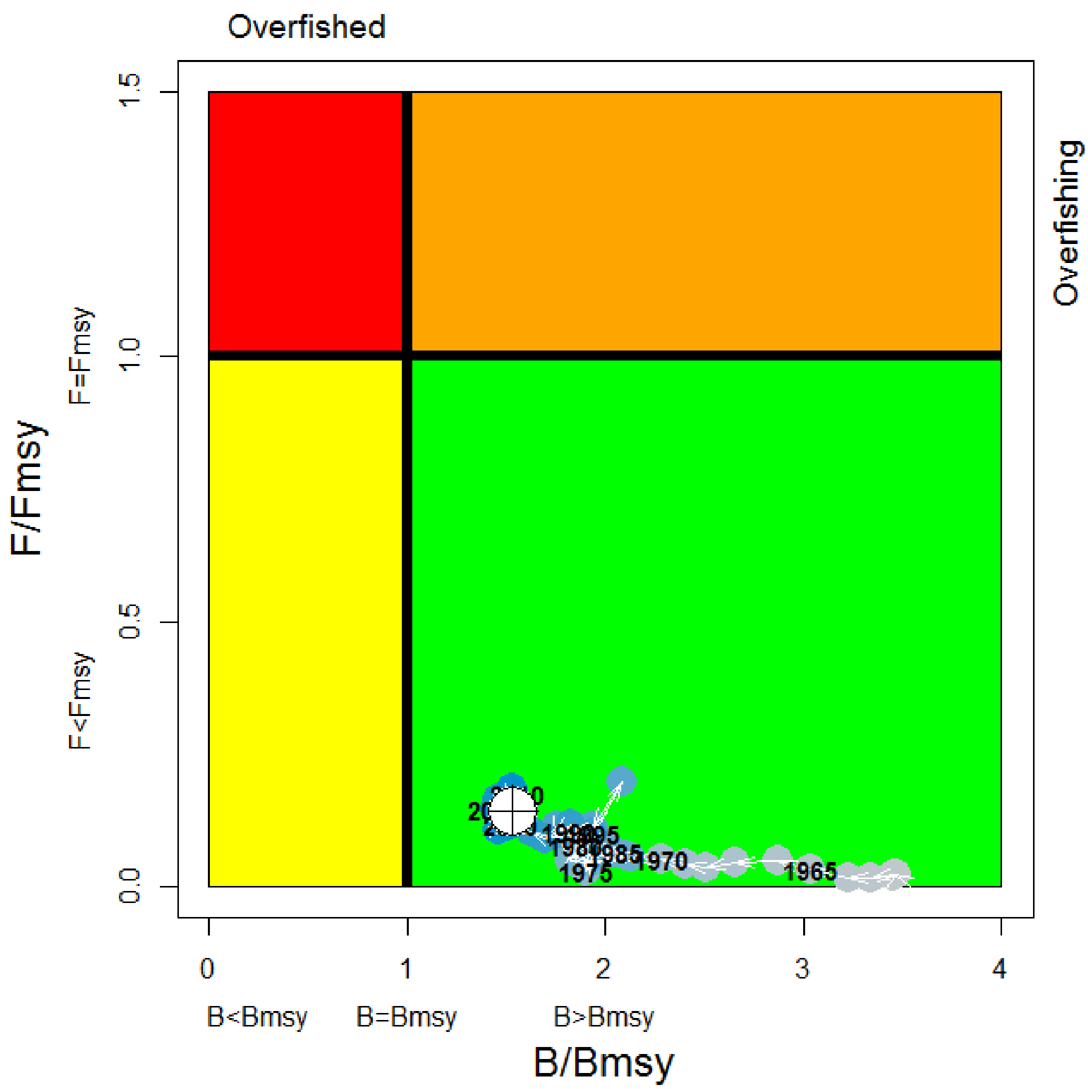


**Figure 47: Temporal trend in annual stock status, relative to $B_{MSY}$ (x-axis) and $F_{MSY}$ (y-axis) reference points, for the model period (starting in 1960). The colour of points is graduated from lavender (2006) to blue (2009) and white cross (2010), and points are labelled at five-year intervals. The last year of the model (2011) is excluded because it is highly uncertain.**

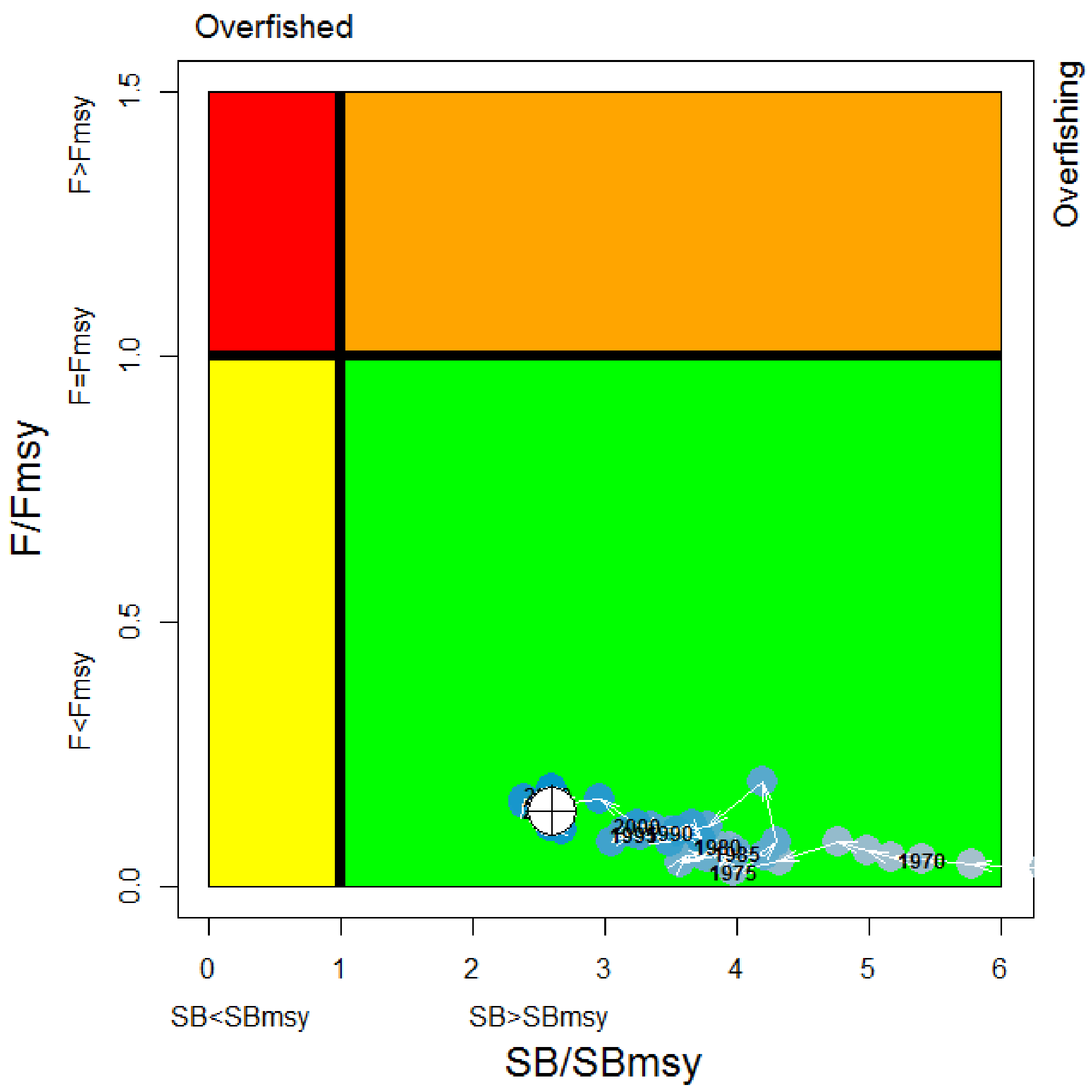


**Figure 48: Temporal trend in annual stock status, relative to $SB_{MSY}$ (x-axis) and $F_{MSY}$ (y-axis) reference points, for the model period (starting in 1960). The colour of the points is graduated from lavender (1960) to blue (2009) and white cross (2010), and points are labelled at five-year intervals. The last year of the model (2011) is excluded because it is highly uncertain.**

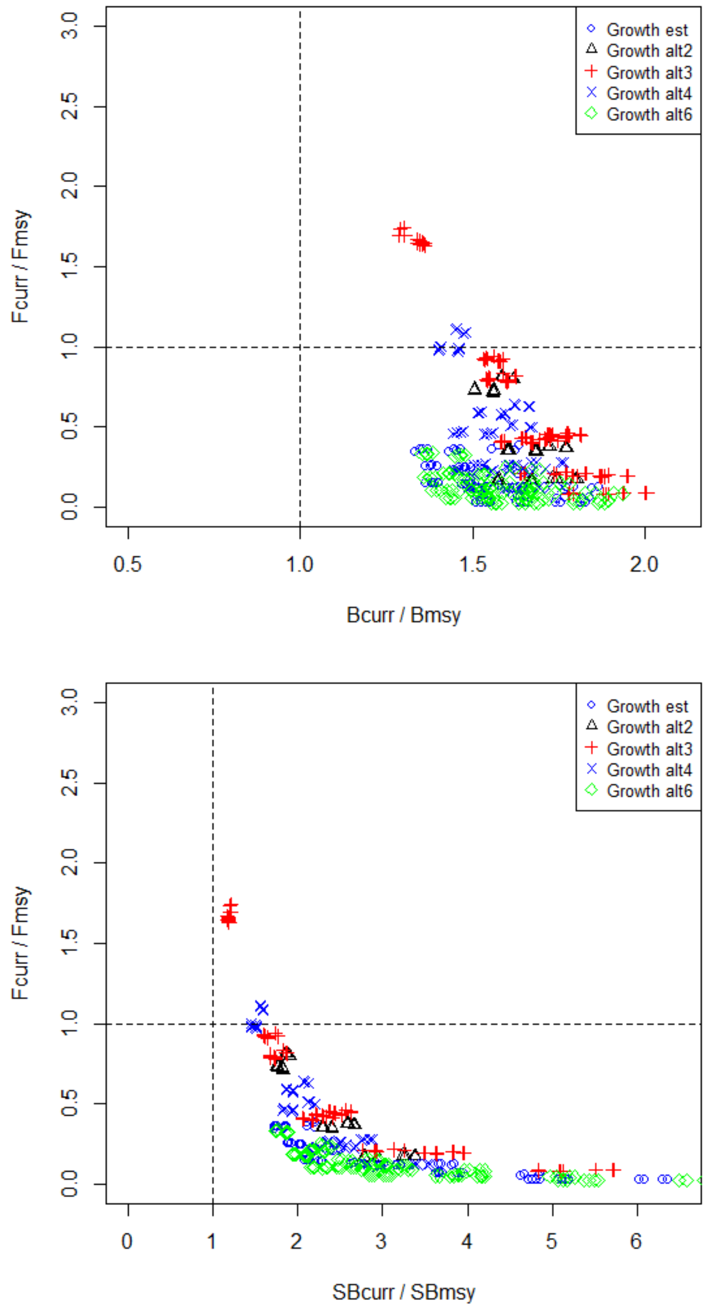


**Figure 49: Scatter plots of values estimated under a grid of scenarios for steepness, assumptions about growth, effort creep, natural mortality, CPUE, and early CPUE. Response variables are a) $F_{current}$ / $F_{MSY}$ versus the biomass depletion ratio $B_{current}$ / $B_{MSY}$, and b) $F_{current}$ / $F_{MSY}$ versus the spawning potential depletion ratio $SB_{current}$ / $SB_{MSY}$.**

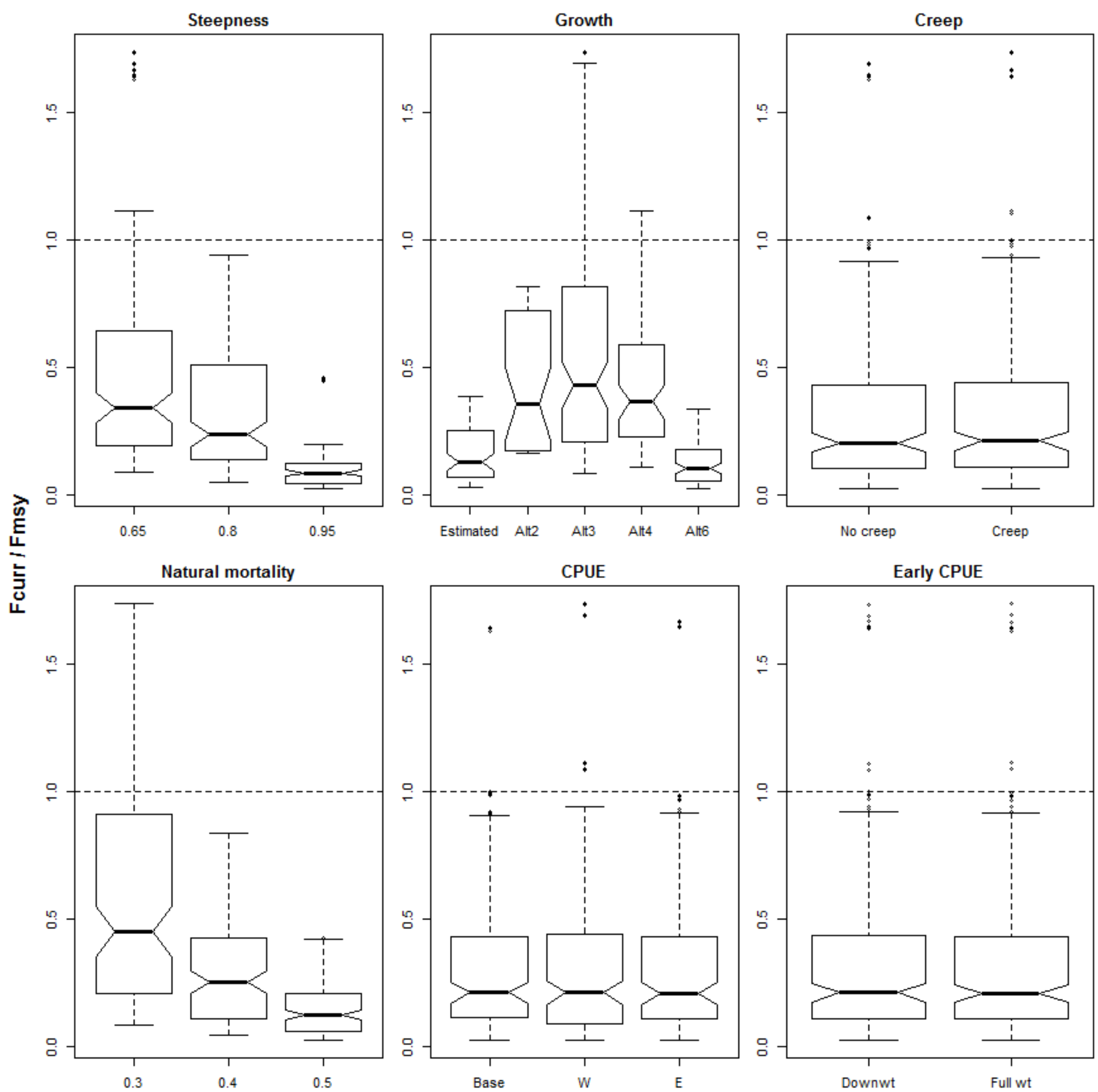


**Figure 50: Box and whisker plots indicating the distribution of the fishing mortality ratio $F_{\mathrm{currrent}}$ / $F_{MSY}$ estimated under a grid of scenarios for steepness, assumptions about growth, effort creep, natural mortality, CPUE, and early CPUE.**

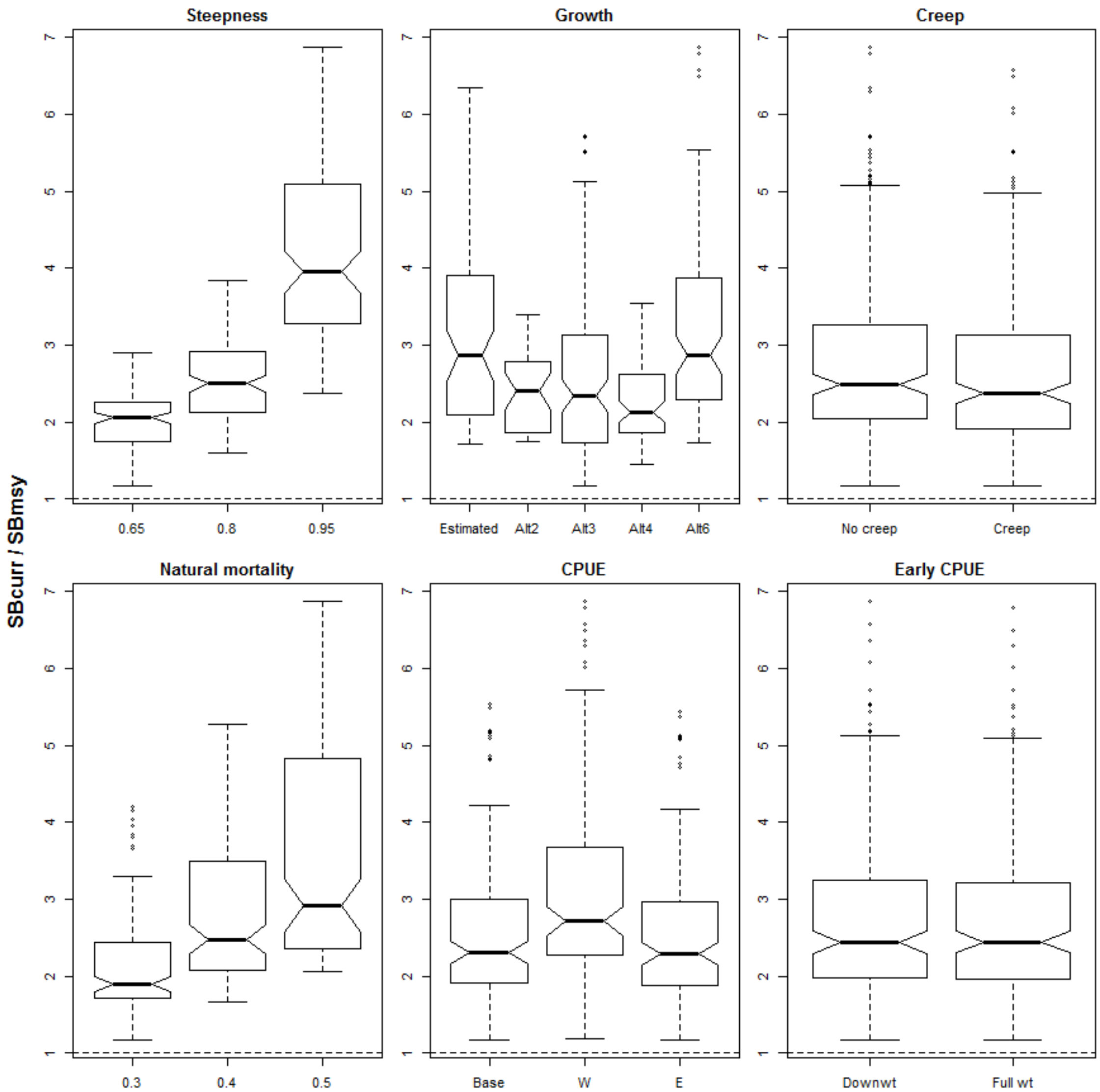


**Figure 51: Box and whisker plots indicating the distribution of the spawning potential depletion ratio $SB_{\text{current}}$ / $SB_{MSY}$ estimated under a grid of scenarios for steepness, assumptions about growth, effort creep, natural mortality, CPUE, and early CPUE.**

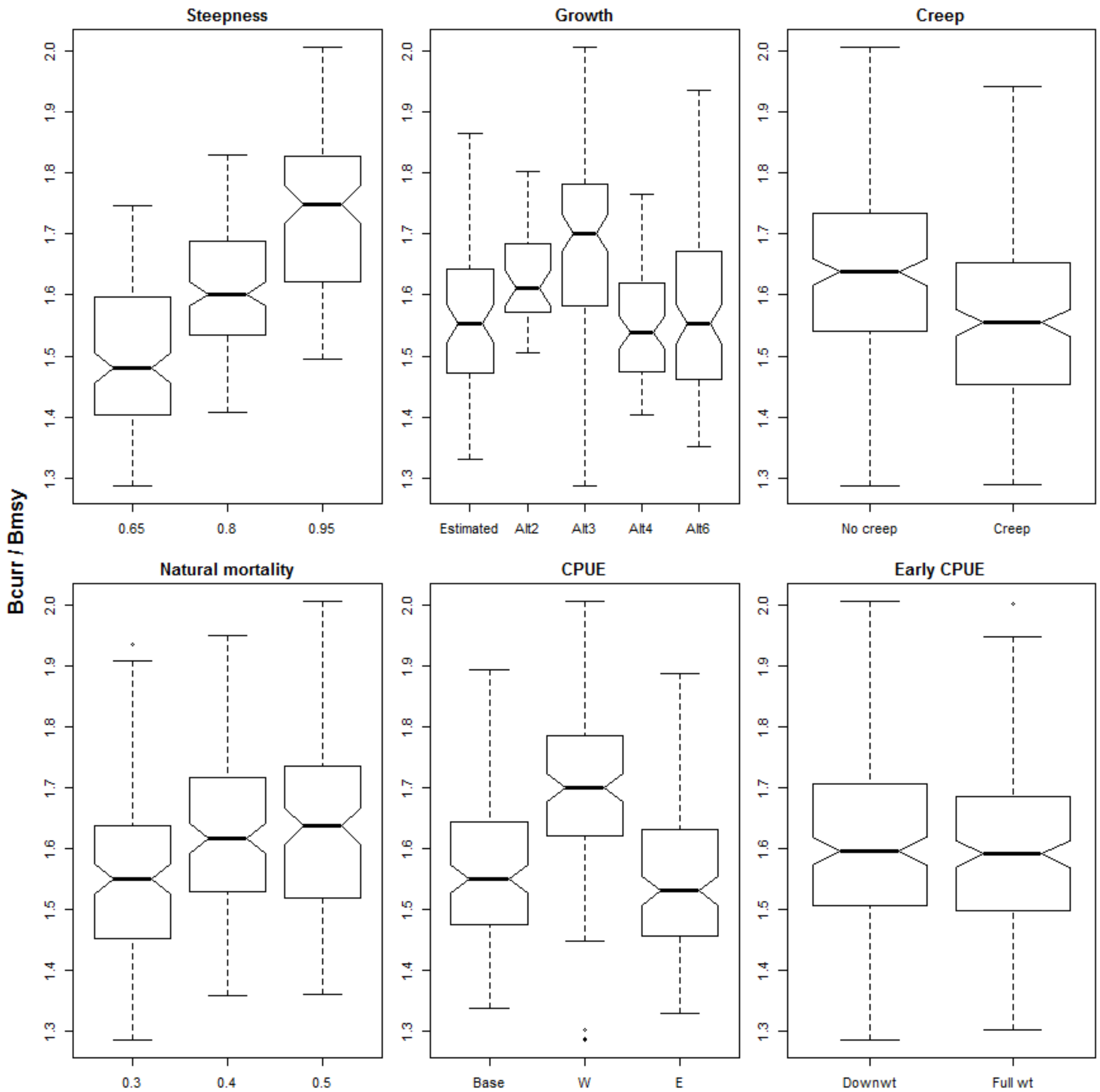


**Figure 52: Box and whisker plots indicating the distribution of the biomass depletion ratio $B_{current}$ / $B_{MSY}$ estimated under a grid of scenarios for steepness, assumptions about growth, effort creep, natural mortality, CPUE, and early CPUE.**

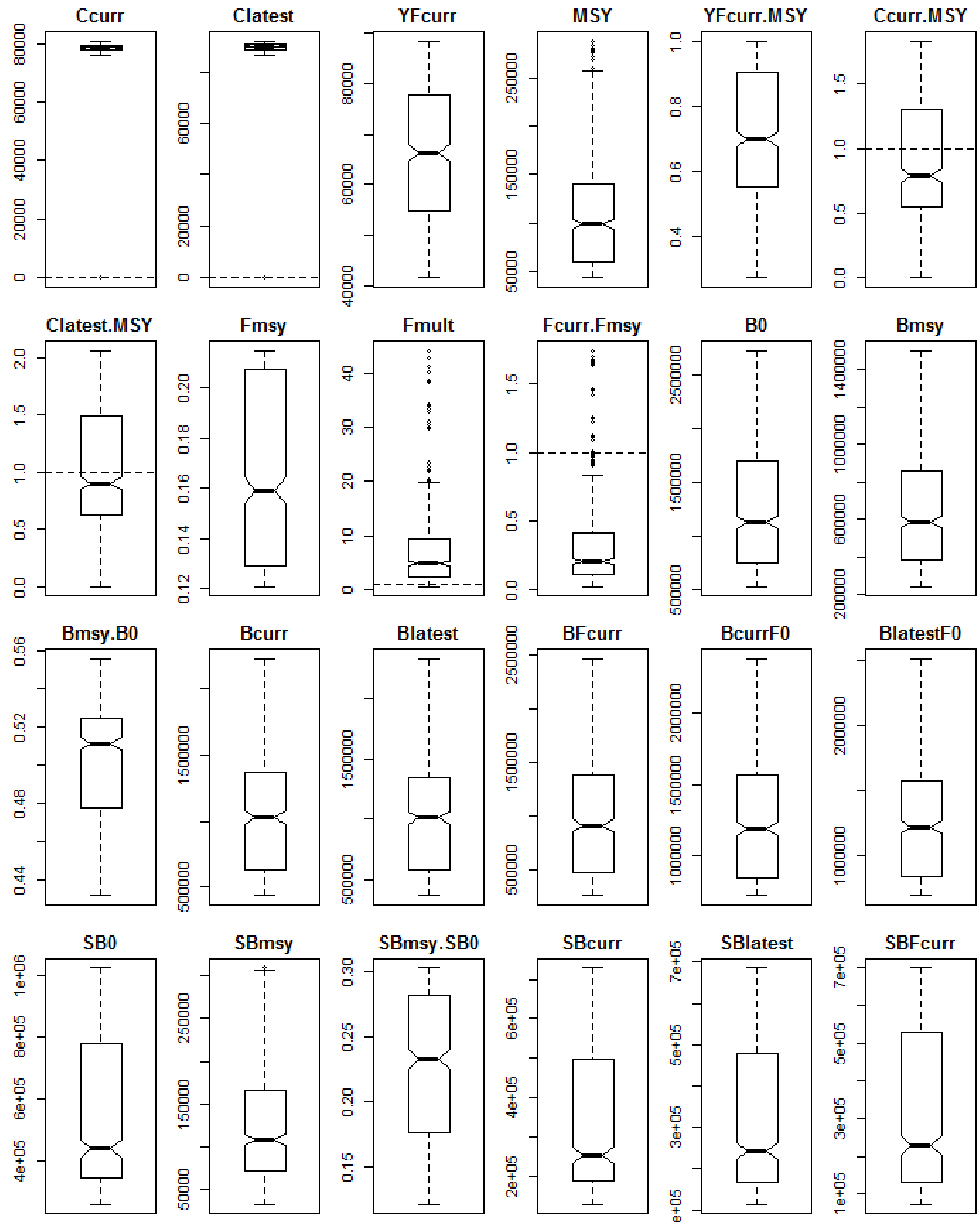


**Figure 53: Box and whisker plots indicating the distribution of management-related parameters under a grid of scenarios for steepness, assumptions about growth, effort creep, natural mortality, CPUE, and early CPUE.**


**Figure 54: Box and whisker plots indicating the distribution of management-related ratios estimated under a grid of scenarios for steepness, assumptions about growth, effort creep, natural mortality, CPUE, and early CPUE.**

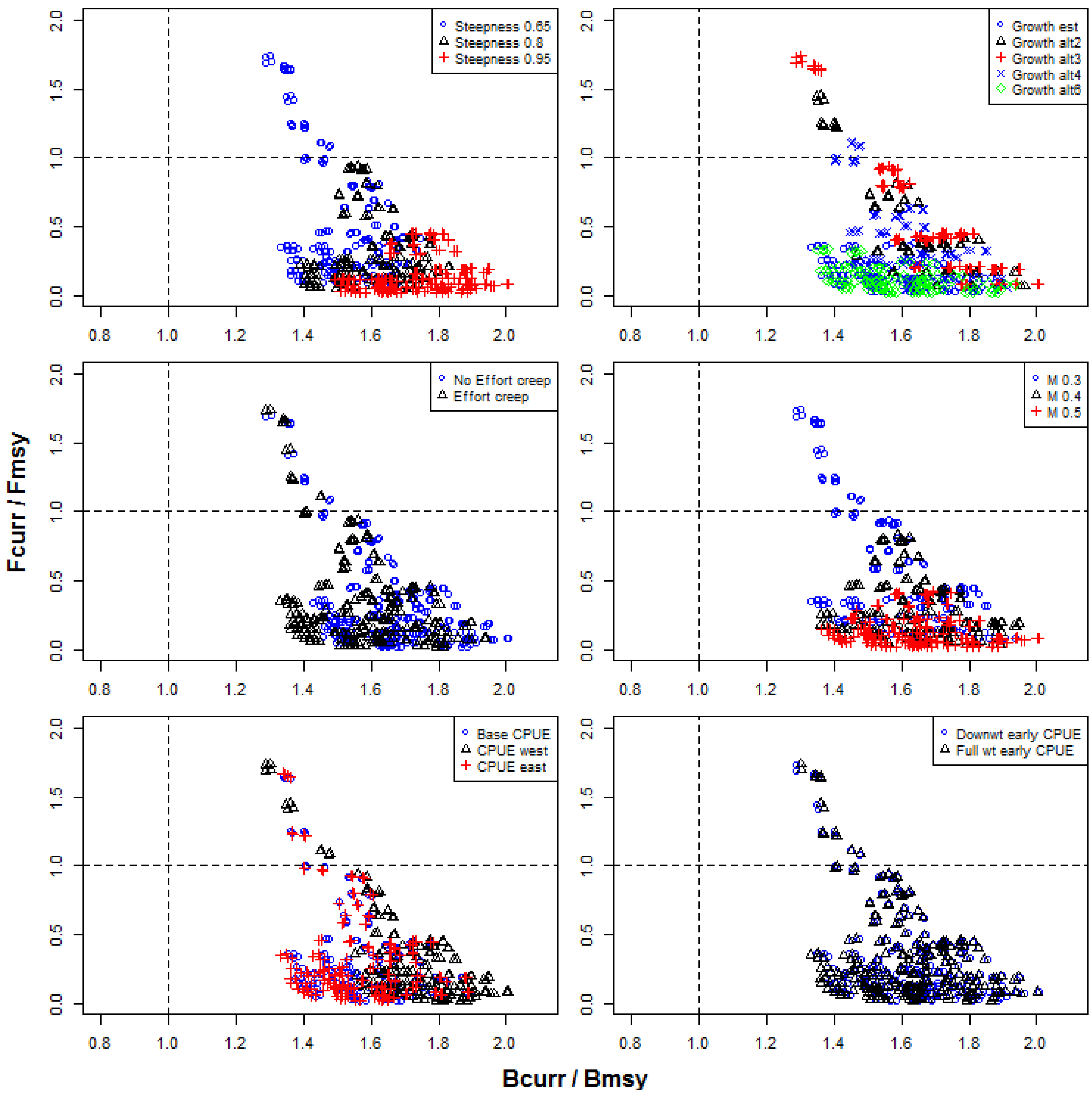


**Figure 55: Scatter plots of values estimated under a grid of scenarios for steepness, assumptions about growth, effort creep, natural mortality, CPUE, and early CPUE. Response variables are $F_{current}$ / $F_{MSY}$ versus the spawning potential depletion ratio $SB_{current}$ / $SB_{MSY}$.**

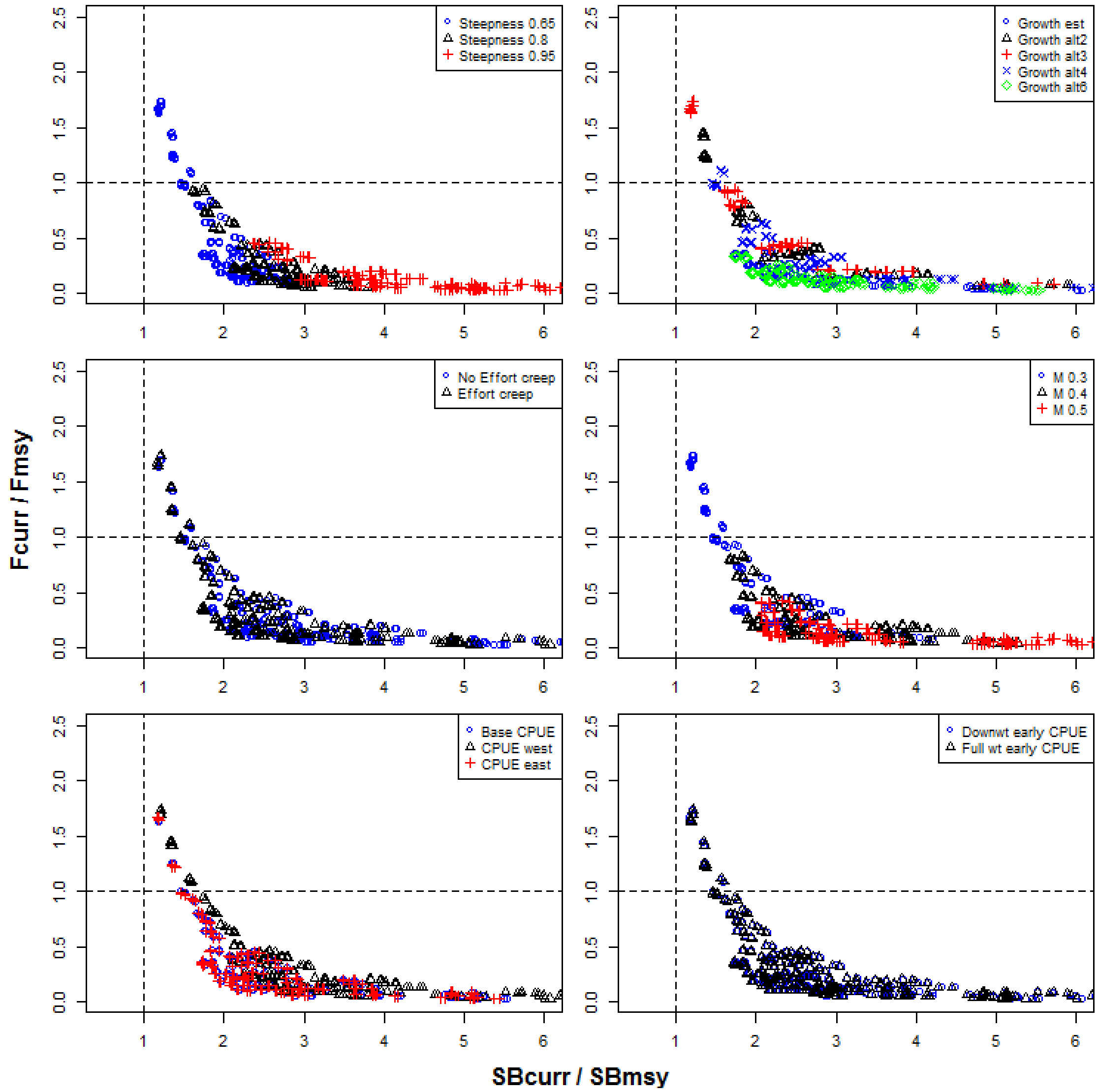


**Figure 56: Scatter plots of values estimated under a grid of scenarios for steepness, assumptions about growth, effort creep, natural mortality, CPUE, and early CPUE. Response variables are $F_{current}$ / $F_{MSY}$ versus the biomass depletion ratio $SB_{current}$ / $SB_{MSY}$**