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**STOCK ASSESSMENT OF STRIPED MARLIN (*Kajikia audax*) IN THE SOUTHWEST
PACIFIC OCEAN**

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Executive summary

This paper presents the 2012 assessment of striped marlin in the south-western Pacific Ocean updating the previous assessment done in 2006. This assessment is supported by several other analyses which are documented separately, but should be considered when reviewing this assessment as they underpin many of the fundamental inputs to the models. These include standardised CPUE analyses of aggregate Japanese and Taiwanese longline catch and effort data (Hoyle & Davies 2012); standardised CPUE analyses of operational catch and effort data for Australian longline fishery (Robert Campbell 2012); standardized CPUE for the recreational fisheries in Australia (Ghosn et al. 2012) and New Zealand (Holdsworth and Kendrick, 2012), and new biological estimates for growth, the length-weight relationship, and maturity at age (Kopf, 2009, 2011). The assessment includes a series of model runs describing stepwise changes from the 2006 assessment model (bcase06) to develop a new “reference case²” model (Ref.case), and then a series of “one-off” sensitivity models that represent a single change from the Ref.case model run. A sub-set of key model runs was taken from the sensitivities that represent a set of plausible model runs, and these were included in a structural uncertainty analysis (grid) for consideration in developing management advice.

Besides updating the input data to December 2011, the main developments to the inputs compared to the 2006 assessment included:

1. Japanese longline catches for 1952-2011 revised downwards by approximately 50%;
2. nine revised and new standardised CPUE time series (with temporal CVs) derived from:
 - aggregate catch-effort data for Japanese and Taiwanese longline fisheries;
 - operational catch-effort data for the Australian longline fishery;
 - operational catch-effort data for the Australian and New Zealand recreational fisheries.
3. size composition data for the Australian recreational fishery.

The main developments to model structural assumptions were to: fix steepness at 0.8; fix growth at the published estimates; estimate spline selectivities for the main longline fisheries; estimate logistic selectivity for the Australian recreational fishery; include time-variant precision in fitting the model to standardized CPUE indices; and remove conflict among the CPUE indices by taking only the Japanese longline index in model area 2 as being representative for the Ref.case. A summary of these and the alternative assumptions for the other key model runs are provided below:

Component	2006 assessment (bcase06)	2012 assessment (Ref.case)	2012 alternatives
Longline CPUE	Japanese and Australian indices areas 1 - 4, no temporal weighting of standardised effort	Japanese indices area 2 only, temporal weighting of standardised effort	<ul style="list-style-type: none"> - Japanese aggregate indices area 1 only - Japanese aggregate indices area 3 only - Japanese aggregate indices area 2 and Australian indices areas 2 and 3
Steepness	Estimated	Fixed = 0.8	0.65, 0.95
Selectivity	Logistic for most fisheries	Logistic for recreational fisheries only	Logistic for recreational fisheries and longline fisheries in area 3
Growth	Fixed $k=0.6$, estimate $L_{\min, \max}$	Fixed at Kopf estimates	Fixed $k=0.6$, estimate $L_{\min, \max}$
Size data	High weight	Moderate weight	Down-weighted
Natural mortality	0.4	0.4	0.2, 0.6

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.

The primary factors causing the differences between the 2006 and 2012 assessments are:

- The approximately 50% reduction in Japanese longline catches over the entire model time period;
- The faster growth rates;
- Steepness fixed at 0.8 rather than estimated (0.546);
- Selectivities for the major longline fisheries use cubic splines, and are not constrained to be asymptotic;
- Removing conflict among the CPUE indices by separating conflicting indices into different models.

Together these changes produce an estimated absolute biomass that is around 30% lower than the 2006 base case and MSY is estimated to be 20% lower. Current biomass levels are higher relative to the MSY reference point levels.

The main conclusions of the current assessment (based upon the median of the uncertainty grid estimates, and the plausible range of key model runs) are as follows.

1. The decreasing trend in recruitment estimated in the 2006 assessment remains a feature of the current assessment, particularly during the first 20 years. It is concurrent with large declines in catch and CPUE in the Japanese longline fishery in area 2. Recruitment over the latter 40 years of the model period declines slightly.
2. Estimates of absolute biomass were sensitive to assumptions about selectivity and to conflicts among the standardized CPUE time series. The reference case model (Ref.case) estimated selectivity functions that decrease with age for the main longline fisheries that achieved the best fit to the size data. The CPUE time series for the Japanese longline fishery in area 2 was selected for fitting the Ref.case model because this time series was considered to be the most representative of changes in overall population relative abundance. Alternative options for selectivity assumptions and the CPUE time series included in the model fit were explored in sensitivity and structural uncertainty analyses, and are presented as the key model runs.
3. Estimates of equilibrium yield and the associated reference points are highly sensitive to the assumed values of natural mortality and, to a lesser extent, steepness in the stock-recruitment relationship. Estimates of stock status are therefore uncertain with respect to these assumptions.
4. If one considers the recruitment estimates since 1970 to be more plausible and representative of the overall productivity of the striped marlin stock than estimates of earlier recruitments, the results of the ‘msy_recent’ analysis could be used for formulating management advice. Under this productivity assumption MSY was 16% lower than the grid median value, but the general conclusions regarding stock status were similar.
5. Total and spawning biomass are estimated to have declined to at least 50% of their initial levels by 1970, with more gradual declines since then in both total biomass ($B_{current}/B_0=36\%$) and spawning biomass ($SB_{current}/SB_0=29\%$).
6. When the non-equilibrium nature of recent recruitment is taken into account, we can estimate the level of depletion that has occurred. It is estimated that, for the period 2007-2010, spawning potential is at 43% of the level predicted to exist in the absence of fishing, and for 2011 is at 46%.
7. The attribution of depletion to various fisheries or groups of fisheries indicates that the Japanese longline fisheries have impacted the population for the longest period, but this has declined to low levels since 1990. Most of the recent impacts are attributed to the ‘Other’ group of longline fisheries in areas 1 and 4, and to a lesser extent the ‘Other’ and Australian fisheries in areas 2 and 3.
8. Recent catches are 20% below the MSY level of 2182 mt. In contrast, the ‘msy-recent’ analysis calculates MSY to be 1839 mt, which places current catches 5% below this alternative MSY level. **Based on these results, we conclude that current levels of catch are below MSY but are approaching MSY at the recent [low] levels of recruitment estimated for the last four decades.**

9. Fishing mortality for adult and juvenile bigeye tuna is estimated to have increased continuously since the beginning of industrial tuna fishing. Apart from those model runs that assumed lower natural mortality or steepness, $F_{current}/F_{MSY}$ was estimated to be lower than 1. For the grid median, this ratio is estimated at 0.58. **Based on these results, we conclude that overfishing is not occurring in the striped marlin stock.**
10. The reference points that predict the status of the stock under equilibrium conditions at current F are $B_{F_{current}}/B_{MSY}$ and $SB_{F_{current}}/SB_{MSY}$. The model predicts that at equilibrium the biomass and spawning biomass would increase to 129% and 144%, respectively, of the level that supports MSY. This is equivalent to 39% of virgin spawning biomass. Current stock status compared to these reference points indicates that the current total and spawning biomass are close to the associated MSY levels ($\frac{B_{current}}{B_{MSY}} = 0.96$ and $\frac{SB_{current}}{SB_{MSY}} = 1.09$). The structural uncertainty analysis indicates a 50% probability that $SB_{current} < SB_{MSY}$, and 6 of the 10 key model runs indicate the ratio to be < 1 . **Based on these results above, and the recent trend in spawning biomass, we conclude that striped marlin is approaching an overfished state.**

This paper also includes a number of recommendations for future stock assessments of striped marlin, including research activities to improve model inputs.

1. Introduction

Striped marlin (*Kajikia audax*) is one of six species of billfishes commonly reported from commercial and recreational fisheries within the western and central Pacific Ocean (WCPO) (Whitelaw 2001, Bromhead et al. 2004, Kopf et al. 2005, Molony 2005). Nearly all commercial catches of striped marlin are made by longline fleets (Bromhead et al. 2004), although small catches of striped marlin have also been reported from purse-seine fisheries of the WCPO (Molony 2005). Striped marlin is also an important recreational species throughout the region (Whitelaw 2001, Bromhead et al. 2004, Kopf et al. 2005).

There is a long history of striped marlin catches by longline fisheries in the southwest Pacific Ocean (Figure 1, Williams 2003) and for some recreational fisheries (Kopf et al. 2005). However, both sectors have shown declines in total catches (Figure 1) and long-term declines in fish size (Kopf et al. 2005, Ward and Myers 2005). In addition, longline vessels in some areas have opportunistically targeted striped marlin (and other billfishes) in the WCPO (e.g. Australia, Bromhead et al. 2004).

Few assessments of striped marlin stocks in the Pacific Ocean have been undertaken. A Pacific-wide striped marlin assessment concluded that longline effort (up to 1980) was well below F_{MSY} (Skillman 1989). Suzuki (1989) considered northern and southern striped marlin as separate stocks and concluded that both stocks were healthy, but the southern stock was being exploited at close to optimum levels (i.e. at about F_{MSY}). Both authors concluded that there were large uncertainties associated with the data sets used. A recent assessment of striped marlin exist for the eastern Pacific Ocean (EPO) concluded that the stock was under-exploited (Hinton and Maunder 2004), while an assessment for the western and central north Pacific striped marlin concluded that the stock was being over-fished and current spawning biomass was in an over-fished state (Brodziak et al. 2012).

This report describes an update from the first stock assessment for striped marlin in the southwest Pacific Ocean undertaken by Langley et al (2006). Substantial new information has been added to the assessment including nine standardised CPUE indices for longline and recreational fisheries, and new input data and biological estimates for growth, the length-weight relationship, and maturity at age. Model assumptions for fisheries selectivity and statistical weighting of the model fit to observations have also been updated.

Much of the background material in this report repeats that of Langley et al (2006) since the biological information remains relevant and the underlying structure of the model is unchanged.

2. Background

2.1. Biology

Striped marlin are a pelagic species with a distribution extending through equatorial to temperate waters, although highest catches and catch rates occur within subequatorial and subtropical areas, particularly in the Pacific Ocean (Nakamura 1985). Most catches of striped marlin have been reported from surface waters (less than 100 m deep) (Brill et al. 1993, Domeier et al. 2003). From archival tagging data, striped marlin spend most time within surface waters (less than 10 m deep), with most dives not exceeding 40 m. Occasional dives have been reported to depths of 40–100 m (Domeier et al. 2003). The habitat preference of striped marlin makes them vulnerable to surface fisheries (longline, recreational and purse-seine method fisheries) from a relatively young age.

Details of the biology and ecology of striped marlin are poorly known, mainly as a result of their relatively low abundances, low catch rates, highly mobile nature and low priority for research funding. Based on the observed distribution of larval striped marlin, spawning occurs between May and June in the north-western Pacific (10–30°N), June–November in the central-eastern Pacific and between November and December in the southwest Pacific Ocean (10–30°S) (Nakamura 1985). A recent study identified larval fish in waters at the mouth of the Gulf of Mexico, eastern Pacific (González Armas et al. 1999). Based on size frequency distribution of female eggs, Eldridge and Wares (1974) suggest that spawning occurs once per season. However, conclusive results are yet to be obtained and further research is required. Most reproduction appears to be limited to spring periods (Nakamura 1985). Based on length data from the Japanese distant water fleet (see Section 3.5), juvenile striped marlin are predominantly captured in the tropical regions of the Pacific Ocean and recruiting to the longline fishery at approximately 80–100 cm in length (eye orbit–fork length, EFL).

Striped marlin display very high initial growth rates, attaining up to 45% of their maximum size in the first year of life (Melo-Barrera et al. 2003). Recent studies in the southwestern Pacific have indicated faster initial growth with fish attaining 70–75% of their maximum size by the second year of life (Kopf et al. 2009, 2011). Growth rates of striped marlin are lower following the onset of maturity (Melo-Barrera et al. 2003, Kopf 2009). Striped marlin mature at around 140–180 cm EFL and 27–40 kg – approximately 2 years of age (Skillman and Yong 1976, Nakamura 1985, Kopf 2011). Sexual differences in growth rates have been reported, and females tend to be heavier than males (Kopf et al. 2011). Striped marlin live for at least 10–12 years (Melo-Barrera et al. 2003, Kopf et al. 2005, 2011) and can exceed more than 300 cm (lower jaw–fork length, LJFL) and 240 kg.

Large striped marlin tend to move further into temperate regions on a seasonal basis, especially in the southern WCPO. Relatively large fish are captured by the recreational fisheries in northern New Zealand (Kopf et al. 2005), and by recreational and commercial fisheries off south eastern Australia, with highest catch rates reported during the first two quarters of the year. While several large movements have been reported from fish tagged and released from northern New Zealand (e.g. several recaptures from waters of French Polynesia), clear migration pathways have not been established. Few large-scale movements have been recorded for marlin tagged off eastern Australia, creating some uncertainty about the extent of mixing of fish within the region. Current tag-recapture data suggest some level of broader sub-regional fidelity, however the recent deployment of numerous archival/satellite tags in marlin off eastern Australia and northern New Zealand should increase our understanding of movement and mixing of striped marlin in the southwest Pacific Ocean (Bromhead et al. 2004). In the southwest Pacific Ocean, it is speculated that post-spawning striped marlin move south-eastwards from the Coral Sea into waters around northern New Zealand and south-eastern Australia to feed and recover, before returning to spawning grounds the following spawning season (Kopf et al. 2005, 2009).

Estimates of mortality rates of striped marlin are rare and have generally been generated from modes identified in length-frequency samples. Estimated natural mortality rates (M) vary between sexes, being lower in males (0.57–0.79 year⁻¹) than females (0.82–1.33 year⁻¹) (Boggs 1989, Pauly 1980, in Hinton

and Bayliff 2002). However, the mortality rates of striped marlin unable to be sexed or of unreported sex have been estimated to be lower ($0.39\text{--}0.49\text{ year}^{-1}$) (Boggs 1989, Pauly 1980, in Hinton and Bayliff 2002). Unsexed fish may be dominated by small, juvenile fish and thus the associated total mortality rates are likely to be lower as few striped marlin below 100 cm EFL are captured by longline fisheries. A meta-analysis of natural mortality estimates for striped marlin proposes a weighted mean value of 0.38 (Piner and Lee, 2010).

The stock structure of striped marlin in the Pacific Ocean is uncertain (Bromhead et al. 2004). A range of stock structures have been proposed for striped marlin in the Pacific Ocean (Graves and McDowell 2003), including a single Pacific-wide stock and a two stock (northern and southern hemisphere) model (Hinton and Bayliff 2002). However, a number of recent studies have strengthened arguments for the occurrence of a semi-independent stock in the southwest Pacific. Conventional tag recapture data indicated no trans-basin movements by striped marlin tagged in the southwest Pacific. This contrasts tag-recapture trends for the two other Pacific marlin species, black and blue marlin. A summary of striped marlin tagging using pop-off satellite archival tags within a state-space model indicates complex temporal-spatial patterns in striped marlin distribution, with strong seasonal patterns by latitude (Chambers et al. 2012). Results of genetic analyses suggest the potential for a significant degree of stock structuring within the Pacific Ocean and support the assumption of a semi-independent stock in the southwest Pacific Ocean (Graves and McDowell, 1994).

Examination of the Pacific-wide spatial trends in Japanese longline CPUE over the past 50 years also supports an argument for stock structuring (Nakamura 1985). Very low catch rates of striped marlin have been reported by longline fleets in equatorial regions of the Pacific Ocean ($10^{\circ}\text{N}\text{--}10^{\circ}\text{S}$, Nakamura 1985) despite considerable longline effort. In contrast, high catch rates have been reported adjacent to the Baja coast of the EPO (Nakamura 1985, Hinton and Bayliff 2002). In summary, current information suggests the potential for at least northern and southern stocks of striped marlin in the Pacific Ocean, with stock structure in the eastern Pacific being unclear.

2.2. Fisheries

Striped marlin are captured mainly by longline fisheries, and to a lesser extent by sportfisheries throughout their range in the southwestern Pacific Ocean (Figure 1). Relatively high catches of striped marlin were estimated during the 1950s and early 1960s, with a peak of more than 6,000 mt estimated for 1954. Since the mid 1960s, catches from the southwest Pacific Ocean have varied between approximately 1,500 mt and 3,000 mt with a decreasing trend since the late 1990s (Figure 1). Much of this decline is attributable to lower catches in the Japanese longline fishery.

Catches of striped marlin were dominated by the Japanese longline fleet until the early 1990s (Figure 1). Taiwanese and Korean fleets have reported moderate to large catches of striped marlin since the mid 1960s and mid 1970s, respectively in the northern and eastern areas. Taiwanese catches have increased in recent years, mainly due to the high effort of this fleet in the eastern temperate WCPO, targeting mainly albacore tuna. Reductions in these catches in the last 5 years have been offset by recent increases in catches in the Chinese longline fishery. Longline fleets of Pacific Island Countries and Territories (PICTs), and by Australia and New Zealand, have reported increasing catches since the early 1990s mainly due to the development of these domestic fleets. Catches by Australian longline fleets have rapidly increased until 2003 due, at least in part, to specific targeting of striped marlin by some vessels during some periods. These catches have declined and stabilized since that time. Since 1987, longline fleets operating in the New Zealand EEZ have been prohibited from landing striped marlin in an attempt support recreational fisheries in the north of the country (Kopf et al. 2005).

Extensive recreational fisheries exist throughout the southwest Pacific Ocean (Whitelaw 2001, Bromhead et al. 2004, Kopf et al. 2005) although total catches by recreational fisheries are very small relative to commercial catches. In addition, a high proportion of striped marlin are (tagged and) released by recreational fisheries in the WCPO (up to 60%, Holdsworth and Saul 2003, in Kopf et al. 2005). However, studies into the survival of recreationally captured marlin have estimated that between 0–50%

of marlin suffer post-release mortality due to hook damage, stress or increased susceptibility to predation (Pepperell and Davis 1999). Although studies are rare, sample sizes are typically small and the durations of monitoring of post-released fish are relatively short (e.g. maximum of 93 days for striped marlin, Domeier et al. 2003). Brodziak (2012) has calculated a mean post-release mortality rate of 25.4% for striped marlin from a meta-analysis of PSAT data.

2.3. Tagging data

A comprehensive summary of available striped marlin tagging data was provided by Langley et al. (2006).

While MULTIFAN-CL has the capability to integrate tagging data in the assessment model, the tagging data from the striped marlin fishery have limited direct application in the current assessment procedure. Nevertheless, the tag data are useful in consideration of the appropriate regional structure for the model. Available satellite tagging data have been summarized in a state-space model (Chambers et al. 2012) that illustrates temporal and spatial complexity (including evidence of seasonal movement) in striped marlin distribution in the southwestern Pacific Ocean. However, within this complexity there was no clear basis for defining discrete stocks within the region. This model did not change the general view gained from conventional tagging data that, while striped marlin were able to make rapid and/or long-distance movements after tagging, almost all recoveries of fish tagged within the region were reported within the model region, indicating a relatively high level of fidelity or probability of occurring within the assessment region (Langley et al. 2006). Further, most tagged fish recaptured in the second or third quarter following release had moved a considerable distance (500–1500 km) indicating strong seasonal movements (mainly south-north) and, thereby, suggestive of a relatively high level of regional-scale mixing of fish in the population. This observation provides support for the adoption of a single model region (see Section 3.1). It may now be possible to use the tagging data to estimate sub-regional movement rates for use in a spatially explicit model. This is area of potential future research.

3. Spatial structure, data sources and compilation

Data used in the striped marlin assessment for the southwest Pacific Ocean consisted of fishery-specific catch and effort data, length-frequency data, weight-frequency data and tag-release-recapture data.

3.1. Spatial stratification

The stock assessment of striped marlin in the southwest Pacific Ocean covered the area from the equator to latitude 40°S and from 140°E to 130°W (Figure 2). This represents the region of the southwest Pacific Ocean where most striped marlin catches have been reported since 1952. The assessment region excluded areas to the north and east due to little evidence for mixing between these regions (Bromhead et al., 2004). Few striped marlin have been reported from Australian longline fisheries south of 40°S, or New Zealand longline fisheries south of 38°S. Overall, the assessment region is considered to encompass a semi-independent stock of striped marlin and, given the spatial distribution of the catch, represents an appropriate spatial scale for assessment and management of the striped marlin resource in the southwest Pacific Ocean.

The assessment modeled a single population of striped marlin within the region, assuming virtually instantaneous mixing of fish throughout the region. However, four sub-areas were defined within the region based on qualitative and quantitative assessments of the distribution of fishing effort and catch for the major fleets, the size composition of the catch (Figure 3) and the qualitative assessment of available tagging and recapture data (Langley et al. 2006). These sub-areas were used to define the spatial boundaries of the individual fisheries operating within the assessment region. Separate selectivity functions were estimated for almost all the fisheries in each sub-area, with seasonal catchabilities being estimated for all fisheries. As such, these parameters may offer, to some extent, a description of age-specific, temporal and spatial patterns in the availability of striped marlin to the various fisheries distributed within the model region.

Fleets operating within the equatorial sub-area of the model (sub-area 1) generally target bigeye and yellowfin tunas, with striped marlin being a commercially important bycatch species for most fleets. Japanese vessels have been the dominant fleet within sub-area 1. However, vessels from other distant-water fishing nations have also operated within the sub-area. In addition, domestic fleets of PICTs in the region have developed during the 1990s. Fleets in sub-area 1 have reported moderate catches of striped marlin dominated by small individuals, but since 2003 these fleets accounted for the largest catches within the region (Figure 3 and Figure 4).

The highest catches of striped marlin have been reported from sub-area 2 of the model region (Figure 4). Longline fleets in sub-area 2 target bigeye and yellowfin tunas, or albacore tuna, with striped marlin being a commercially important bycatch species. Historically, Japanese vessels were the dominant fleet in this sub-area. However, Japanese effort has declined in this sub-area since the early 1990s. The Australian longline fleet and longline fleets of other PICTs within the sub-area have expanded the mid-1990s. Some vessels within the Australian longline fleet have opportunistically targeted striped marlin in recent years within this sub-area and in sub-area 3. Total catches in this sub-area have been declining since a peak in 1997. Catches of striped marlin from sub-area 2 are dominated by relatively large fish.

Catches of striped marlin from sub-area 3 are also dominated by large fish. The Japanese fleet was the dominant fleet in this sub-area until the 1990s. The Australian domestic fleet accounts for most of the recent catches of striped marlin from sub-area 3. With the exception of the Australian fleet, longline fleets in this region do not specifically target striped marlin; it is prohibited to commercially retain striped marlin within the New Zealand EEZ (Kopf et al. 2005). Significant recreational fishing effort also occurs in this sub-area (Figure 4), focused in northern New Zealand and the central-eastern coast of Australia, with striped marlin being a major target species (Bromhead et al. 2004, Kopf et al. 2005). Catches from sub-area 3 are currently of a similar magnitude to those from sub-area 2 (Figure 4).

Catches of striped marlin are relatively low from sub-area 4 (Figure 4). Only the distant water fleet of Taiwan has reported relatively high levels of effort from this sub-area; targeting albacore tuna. Longline fleets of PICTs also operate in sub-area 4, targeting mainly albacore tuna. However, striped marlin contributes to the retained commercial bycatch by longline fleets within this sub-area. Recreational fisheries also exist within this sub-area but the total catch from these fisheries are relatively insignificant. Limited size data were available for this sub-area of the model.

3.2. Temporal stratification

Data used in the current analyses covered the period 1952–2011. Catches of striped marlin display strong seasonal variations (Bromhead et al. 2004, Kopf et al. 2005) particularly at the more southern latitudes of their range. Further, some fisheries show strong seasonal variations in effort (e.g. Taiwan distant water fleet, Australian and New Zealand recreational fisheries). As a result, data were divided into quarters (January–March, April–June, July–September, and October–December).

3.3. Definition of fisheries

The sub-areas of the model region were applied to define the spatial boundaries of the specific fisheries in the southwest Pacific Ocean. A total of 12 longline fisheries and 2 recreational fisheries were defined (Table 1), based on sub-area boundaries, fishing method and nationality.

The Japanese longline fleet has dominated the effort for, and catches of, striped marlin in the assessment region throughout the time series so a separate Japanese fishery was defined for each sub-area (Fisheries 1–4). A separate Taiwanese fishery (Fishery 5) was defined for sub-area 4 as this fleet has dominated effort and catches of striped marlin in the sub-area, particularly since the mid 1970s (Figure 4). Since the early 1990s, major longline fisheries have also developed in Australia (one fishery in each of sub-areas 2 and 3, Fisheries 6 and 7) and New Zealand (one fishery in sub-area 3, Fishery 8). Four additional longline fisheries were defined to account for the other sources of longline effort and catch in each of the four sub-areas (Fisheries 11–14, Table 1). These other longline fisheries included effort and catches by recently developed longline fisheries of PICTs.

Major recreational fisheries that target striped marlin were also defined as individual fisheries in sub-area 3 of the assessment model: an Australian recreational fishery (Fishery 9) and a New Zealand recreational fishery (Fishery 10) (Table 1). Other recreational fisheries capturing striped marlin exist in the assessment region (Whitelaw 2001). However, these other recreational fisheries are relatively small and catch and effort data were not readily available.

3.4. Catch and effort data

For all fisheries, catch data were expressed as the number of striped marlin captured (Table 1). For all longline fisheries, fishing effort was defined as the number of hooks set. For recreational fisheries, effort data were supplied as number of days. Catch and effort data for all fisheries were aggregated within the quarterly time intervals.

Data were supplied in a variety of spatial and temporal resolutions. For example, longline catch and effort data from the distant-water fleets were generally available aggregated by month and 5-degree spatial resolution, while operational-level logsheet data were available for many of the domestic longline fleets. Recreational data were supplied for individual sub-areas of the model.

Japanese distant-water longline fisheries (Fisheries 1, 2, 3 and 4, sub-areas 1–4, respectively): Catch and effort data from the Japanese fleet for 1952–2011 were supplied by the NRIFSF stratified by spatial cell (5-degree of latitude and longitude), month, and gear configuration (number of hooks between floats, HBF). The spatial scale of operation of the Japanese longline fleet has declined over the last 20 years. For example, since 1992, limited longline effort was reported by the Japanese fleet in sub-area 4 of the region (Fishery 4).

There is a substantial change in the Japanese catch estimates used in this assessment. The large difference between the total catch (in numbers) used in the 2006 and the 2012 assessments (Figure 5) was due to an error in the preparation of the data used in the 2006 assessment, whereby the catch and effort of two data sources provided for this assessment (JP longline 5°x5°/month and JP longline 1°x1°/month) were mistakenly included when only one of these data sources should have been used. This error resulted in a doubling of catch and effort for Japan longline fleet in the 2006 assessment although the CPUE (catch divided by effort) was correct. This problem was identified and rectified in the preparation of data for the 2012 assessment.

Fishing effort by the Japanese distant-water fleet (Fisheries 1–4) were standardised using a generalised linear model (GLM) approach (Hoyle & Davies, 2012). The GLMs included the following variables: year/quarter, spatial cell (5° latitude/longitude cell), and HBF. The resulting CPUE indices are presented in Figure 6. For each year/quarter, an index of standardised effort was calculated by dividing the total quarterly catch by the CPUE index derived from the GLM model. Estimates of time-variant precision for each standardized index were calculated, with the highest being for those for the early and most recent periods (Figure 7).

Taiwanese distant-water longline fishery (Fishery 5, sub-area 4): Catch and effort data for this fleet were available aggregated by 5-degree square and month. Data were supplied by the National Taiwan University (1967–1993) and by the Overseas Fisheries Council of the Republic of China via the Council of Agriculture (1994–2003). Data were raised to represent total catches (see Lawson (2004) for more information). A GLM approach was applied similar to that described for the Japanese fisheries to derive a standardised CPUE series (Figure 6). The GLM model was limited to include year/quarter and 5-degree spatial cell. Estimates of time-variant precision were calculated. A period of less precise indices was evident during the late 1980s and early 1990s (Figure 7.)

Australian longline fisheries (Fisheries 6 and 7, sub-areas 2 and 3, respectively): Longline catch and effort data were provided on a quarterly basis for each sub-area by the Australian Fisheries Management

Authority (AFMA) for the period 1990–2003. Data were raised to provide estimates of total catches applying the scaling factors used by Campbell et al. (2002).

CPUE indices were provided (Campbell 2012) based upon a two-stage ('delta') GLM approach (Binomial and Log-gamma) applied to operational-level data to derive a standardised effort series for the fisheries in sub-areas 2 and 3. The two GLM models included the following variables: a specific function for the year/quarter/area interaction, HBF, time of set, number of light sticks deployed on the longline, bait type, and a number of environmental factors (Campbell 2012). The resulting CPUE indices are presented in Figure 6 with the time-variant precision estimates in Figure 7.

New Zealand longline fishery (Fishery 8, sub-area 3): Longline data, in both numbers and tonnes of striped marlin, were provided by the Ministry of Fisheries (MFish), New Zealand, for the period 1993–2011. However, the landing of striped marlin by commercial longline vessels fishing within the New Zealand EEZ has been prohibited since 1987 (Kopf et al. 2005). While records of retained and discarded striped marlin do occur in the logsheet data for this fishery, it is likely total catches for this fishery are under-estimated because operational data provided does not represent 100% of the vessels. Therefore, the operational data was raised based on the annual catch estimates provided (i.e. raised by total target tuna annual catch estimates / total target tuna operational data). Only New Zealand longline data north of 38°S were included in the analysis as longline vessels operating further south mainly target southern bluefin tuna and catch very few striped marlin (S. Harley, pers. comm.).

Other longline fisheries (Fisheries 11, 12, 13 and 14, sub-areas 1–4, respectively): Other longline fleets have also operated within the model region since 1952, aside from the fisheries identified above. These "other" longline fisheries were pooled into the relevant model sub-areas on a quarterly basis. Fishery 11 (sub-area 1) included fleets from PICTs (e.g. Papua New Guinea, Solomon Islands, Vanuatu, Cook Islands and French Polynesia), plus fleets from distant water fishing nations other than Japan. Fishery 12 (sub-area 2) included catch and effort data from some PICTs (e.g. New Caledonia, Vanuatu, Fiji and Tonga) plus fleets from distant water fishing nations other than Japan. Fishery 13 (sub-area 3) included all fleets from other than Australia, Japan and New Zealand. Fishery 14 (sub-area 4) included fleets from some PICTs (e.g. Cook Islands, French Polynesia) and all fleets from other distant water fishing nations other than Japan and Taiwan. All data for these other fisheries were supplied as logsheet data and/or aggregated spatial data, with effort and catches raised as appropriate (see Lawson 2004).

Australian recreational fishery (Fishery 9, sub-area 3): A summary of the recreational fishery catch data (1952-2011) and standardized CPUE (1994-2011) was available (Ghosn et al. 2012). The data were collected during game fish tournaments from operators fishing off south-eastern Australia. The GAM indices are presented in Figure 6 and the estimates of time-variant precision in Figure 7.

New Zealand recreational fishery (Fishery 10, sub-area 3): Information for this fishery was supplied by Holdsworth & Kendrick (2012) with catch data for the period 1952–2011 and standardized CPUE indices from 1975-2011. Data were obtained from extensive fishing club records. The GAM indices are presented in Figure 6 and the estimates of time-variant precision in Figure 7.

3.5. Length and weight frequency data

Length-frequency and/or weight-frequency data were available from many of the fisheries defined in Table 1, although data were provided in a number of different formats depending on the specific fishery. For most fisheries, temporal coverage of the size frequency data was relatively limited (Figure 8).

Length data were provided based on three different length measurement methods: eye orbit–fork length (EFL), lower jaw–fork length (LJFL) or pelvic fin–fork length (PFFL). A range of weights were supplied including whole weight, Japanese processed weights (gilled, gutted, head and tail left on, bill removed at a point level with the tip of the lower jaw), and gilled, gutted and headed (i.e. trunked) weights. All length measurements were standardised to EFL and weight measurements were standardised to the equivalent whole (unprocessed) weight.

Japanese longline fisheries (fisheries 1–4, sub-areas 1–4): Data were supplied by the NRIFSF and represented the most extensive size data used in the analysis (approximately 3,000 length measurements and 43,000 weight measurements, Table 2). Length and/or weight data were available from 1970–2005, although coverage varied between sub-areas, and limited data exists after 1998. Length data were recorded as EFL while weight data were supplied as Japanese processed weights. The Japanese style of processing removes the gills, guts, and the bill at the point of the lower jaw, while retaining the head and tail. The following two stage procedures was applied to the processed weights to estimate whole weight.

- Convert from processed weight to whole weight:
 $(\text{Processed weight}) * 1.098 + 3.655$
- Convert whole weights to reverse truncation effect:
 $\text{trunc}(1.1788374 * (\text{WT_GG} + \text{rand}() - 0.5)^{0.9984})$

Australian longline fisheries (fisheries 6 and 7, sub-areas 2 and 3): A large amount of weight data were available from the Australian longline fisheries from AFMA for the period 1997–2011 (Table 2). The weight data was originally sourced from the main fish processors receiving striped marlin from Australian longline vessels and represents a comprehensive sample of the entire catch. Weights were supplied as processed (trunked) weights (i.e. gilled, gutted and head removed) to the nearest 0.1 kg. To enable comparisons with whole weights, a conversion factor was calculated using processed and whole weight data for 254 striped marlin, which were collected by Australian observers on Japanese longline vessels operating in Australian waters in the early 1990s. The relationship between the two measures was:

$$\text{Whole weight (kg)} = 1.1788 \times \text{gilled-gutted weight (kg)}^{0.9984}$$

Until such time as a conversion factor can be calculated directly from data collected on Australian longline vessels, this conversion factor represents the most appropriate (given similarities in fishing methods between the two fleets) and was applied to all processed weights from the Australian longline fisheries prior to analysis.

New Zealand longline fishery (fishery 8, sub-area 3): Nine quarters of length data were available from observers on board New Zealand longline vessels during 1995–2011. Data were supplied by MFish with lengths measured as LJFL and converted to EFL by multiplying by 0.862.

Australian recreational fishery (fishery 9, sub-area 3): Weight frequency data were available for the Australian recreational fishery for the full model period (Ghosn et al 2012). All weights were supplied as whole weights (Table 2) and were from landed fish (therefore accurately measured). Only landed weights were incorporated into the analysis because the tagged component of the catch was not included as fishing mortality.

New Zealand recreational fishery (fishery 10, sub-area 3): Weight data were supplied for the New Zealand recreational fishery (John Holdsworth pers.comm. Blue Water Research Ltd.) that covered the period 1952–2011. All weights were recorded as whole weights and were either from landed fish (therefore accurately measured). Only landed weights were incorporated into the analysis because the tagged component of the catch was not included as fishing mortality.

Other longline fisheries (fisheries 11, 12 and 14, sub-areas 1, 2 and 4): Length data were available from fishery 11 during the period 1996–2011; fishery 12 for 1993–2011, and from fishery 14 for several quarters during 1996–2011. Data from these fisheries were supplied from a combination of regional observer programmes, regional port-sampling programmes and/or from research institutes of distant water fleets. Very limited length and weight data were available for fishery 13 from 2006–2011.

Size data were aggregated by fishery and time strata (year/quarter). Length data were aggregated into 52 6-cm size classes (20–326 cm EFL), which is a more coarse stratification than that used for the 2006 assessment (154 2-cm size classes). Weight data were aggregated into 246 1-kg intervals (5–250 kg whole weight). Length or weight data were not available for all quarters for the period of data supplied

for each fishery (Table 1). The exception was fishery 10 (New Zealand recreational fishery, sub-area 3) for which there were landed weight data in the first quarter for all years with associated weight-frequencies (Figure 8). Fisheries for which comprehensive weight-frequency data available included the LL JP2 & 3, LL AU2 & 3, and the REC NZ3 fisheries; and those with comprehensive length-frequency data available included LL Other1 & 2 (Figure 8, Table 2).

Overall, smaller fish were more commonly captured by longline fisheries in sub-area 1 (equatorial areas) with sequentially larger fish tending to be captured by longline fisheries in more temperate waters of sub-areas 2 and 3 (Figures 3 and 9). Recreational fisheries tended to capture larger striped marlin than the longline fisheries.

Instances of erroneous samples for small fish were identified in the size frequency data and subsequently removed from the samples. For fishery 1 in 1995, a single sample of atypical size composition and exceptionally large sample size (10- to 100-fold higher than in other years) was removed. For fishery 14 in the period 1995 - 2001 samples consisted of only small fish, which was clearly atypical relative to samples in subsequent years. These instances were suggestive of sampling bias and it is likely that these exceptional samples were not representative of the fishery catch composition because they were atypical of other years, or may reflect spatial heterogeneity in size compositions and are most likely not representative. Excluding these potential outliers is unlikely to bias model estimates because growth and natural mortality are assumed at fixed values, and fish in these size classes are only partially recruited to the fishery.

Weight-frequency observations for the REC AU3 fishery collected prior to 1986 had fewer than 30 observations per year, and were collected from a period when the fishery was operating in the northern range of the fishery that is atypical of its core operations since 1986 when most of the catch was taken (Ghosn et al 2012). These observations were detrimental to the model fit to recent data for this fishery and were removed.

3.6. Biological parameters

Parameters such as growth rates, maturity schedule, longevity and mortality are important model parameters for MULTIFAN-CL (Fournier et al. 1998). While MULTIFAN-CL can estimate many of these parameters, starting values are required for all parameters, with some parameters being fixed through time (e.g. growth rate and the maturity ogive).

The values of biological parameters used for fixed or starting values in the 2006 assessment were updated using recently published estimates. Kopf et al. (2009, 2011) provide new estimates for growth rates, the length-weight relationship and maturity-at-age. The ‘back-calculation 1’ growth model, averaged for both sexes, was assumed for this assessment as this model was recommended by Kopf et al (2009) because it accounts for fishing method selectivity bias in observed lengths-at-age. This model predicts significantly faster growth with 1 year-old fish having a mean EFL of 121 cm compared to 60 cm estimated in the 2006 assessment. While the mean lengths-at-age were fixed at the published values, the variances were estimated when fitting the population model.

Similarly, the recently published length-weight relationship predicts heavier fish on average compared to the relationship assumed in the previous assessment. The new biological information does not however alter the maturity-at-age schedule assumed for the previous assessment, and the maximum longevity remains at 10 years of age. Natural mortality was fixed at 0.4 year^{-1} for all age classes.

The formulations and new biological parameters were transformed in terms of EFL and whole weight to be consistent with the units used in the model (Table 3). Plots of the growth functions are presented later in this report.

In contrast with the previous assessment where the steepness of the stock recruitment relationship was estimated with a weakly informative prior, a fixed value of steepness equal to 0.8 was assumed with

alternative options of 0.65 and 0.95 explored in sensitivity analyses. This approach is consistent with that currently applied in tuna stock assessments in the WCPO that regards steepness as a parameter not readily estimable (Harley, 2011).

4. Model description – structural assumptions, parameterisation, and priors

As with any model, various structural assumptions have been made in the southwest Pacific striped marlin model. Such assumptions are always a trade-off to some extent between the need, on the one hand, to keep the parameterization as simple as possible, and on the other, to allow sufficient flexibility so that important characteristics of the fisheries and population are captured in the model. The mathematical specification of structural assumptions is given in Hampton and Fournier (2001). The main structural assumptions used in the striped marlin model are discussed below and summarized in Table 4.

Due to the limited data available and uncertainty concerning some of the key biological parameters, in particular the movement dynamics of the species, a simple model structure was adopted with a single model region, thereby, assuming instantaneous and complete mixing of the population throughout the spatial extent of the model.

A single sex dimension was assumed because MULTIFAN-CL currently does not support multiple sex structure. Model estimates will most likely be biased because sexual dimorphism has been observed in terms of the length-weight relationship (Kopf et al 2011), and there is evidence of spatial heterogeneity in both sex ratios and size composition (authors unpublished data).

There are observed differences in the size (length and/or weight) structure of the catch among sub-areas of the model region (see Figure 3). These spatial differences were addressed through the method and area specific definitions of the fisheries incorporated in the model and the flexibility to estimate specific size-based selectivity functions for each of the main fisheries within each sub-area. Seasonal and spatial variations in catch rates of striped marlin between fisheries are accounted for in the model by estimating fishery-specific catchability parameters incorporating seasonal variation.

The principal source of abundance information in the model is derived from the catch and (GLM standardised) effort series for the main longline fisheries (Figure 7). There were nine standardized effort series available for the model fitting procedure: seven for the longline fisheries (LL JP1 to 4, LL TW4, LL AU2 & 3), and two for the recreational fisheries (REC AU3 and REC NZ3). The most significant and sustained component of the catch from the model region and throughout the time period is from the Japanese longline fisheries in sub-areas 2 and 3 (LL JAP2 & 3). The effort series to be included in the model fit were evaluated in terms of data conflict and this is described later in the results section.

4.1. Observation models for the data

There are three data components that contribute to the log-likelihood function – the total catch data, the weight-frequency data and the length-frequency data. No tagging data were included in the fitting of of this assessment model. The 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.

The probability distributions for the length-frequency proportions are assumed to be approximated by robust normal distributions, with the variance determined by the effective sample size and the observed length-frequency proportion. Effective sample size for the length and weight frequency samples is assumed to be 0.05 and 0.025 (respectively) times the actual sample size for all fisheries, with a maximum effective sample size of 100. Reduction of the effective sample size recognises that size-frequency samples are not truly random and would have higher variance as a result. Length-frequency data from the LL NZ3 fishery has fewer than 30 observations per year. Given that this fishery was assumed to share selectivity patterns with the LL AU 2 fishery, these scant length samples were down-weighted to 0.01 times the effective sample size.

4.2. Recruitment

‘Recruitment’ in terms of the MULTIFAN-CL model is the appearance of age-class 1 fish in the population (Fournier et al. 1998). Striped marlin are known to spawn during November–December in the sub-tropical latitudes of the southwest Pacific (Kopf et al 2011). On this basis, recruitment to the model population was assumed to be an annual event that occurs in November of the year following spawning (i.e. one year old fish).

The time-series variation in recruitment was somewhat constrained by a penalty having a variance equivalent to a CV of about 0.2 (normal scale). This is a moderately restrictive prior for recruitment variation — since recruitment could be expected to vary substantially between years. However, preliminary model runs using a weaker prior revealed a very strong temporal trend in the deviations in recruitment, essentially following the trends in longline CPUE. The penalty was used to mediate this effect in the model.

Recruitment was assumed to be related to spawning biomass according to the Beverton-Holt stock-recruitment relationship (SRR). The SRR was incorporated mainly so that a yield analysis could be undertaken for stock assessment purposes. A relatively weak penalty was applied to deviation from the SRR so that it would have only a slight effect on the recruitment and other model estimates (Hampton and Fournier 2001).

Typically, fisheries data are very uninformative about SRR parameters and it is generally accepted that the steepness parameter is not well estimated in fisheries models. Consequently, a fixed value equal to 0.8 was assumed, with alternatives of 0.65 and 0.95 examined in sensitivity analyses.

4.3. Natural mortality

Natural mortality was set at the assumed value of 0.4 for all age classes. This is the mid-point of the range of natural mortalities for small (relatively unexploited) striped marlin reported by Boggs (1989) and Pauly (1980, in Hinton and Bayliff 2002) for the Pacific Ocean. The approach used in the 2006 assessment was repeated where the sensitivity of the model to the assumed value of natural mortality was examined by comparing the results using values of natural mortality of 0.2 and 0.6 (fixed across all age classes).

4.4. Age and growth

The assumptions made concerning age and growth in the MULTIFAN-CL model are (i) the lengths-at-age are normally distributed for each age class; (ii) the mean lengths at age follow a von Bertalanffy growth curve; and (iii) the standard deviations in length-at-age is a linear function of the mean length-at-age (Fournier et al. 1998). The probability distributions of weights-at-age are a deterministic function of the lengths-at-age and a specified weight-length relationship (Table 3).

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. Striped marlin are thought to have a relatively high natural mortality (Boggs 1989) with few individuals living beyond the ages of four or five years old (Kopf et al 2011) and, consequently, it was considered that 10 yearly age classes (including the 10 year plus group) was sufficient to define the dynamics of the population.

Mean lengths-at-age were fixed using the recently published growth estimates for combined sexes (Kopf et al. 2009, 2011). Model sensitivity to the growth function was examined using an approach that estimated the mean length of the oldest (10+) age-class (essentially the model parameterisation of L_{∞}) and length-at-first-age parameters. The k parameter was fixed at the value 0.6 (Table 3) since this value was within the range of k -values reported by a range of authors (Kopf et al 2011, Boggs 1989, Melo-Barrera et al. 2003, Kopf et al. 2005) and was used in the 2006 assessment (Langley et al. 2006).

4.5. Selectivity

Selectivity is fishery-specific and assumed to be time-invariant and length-based but modelled as age-based (Kleiber et al. 2003). Differences in selectivities among fisheries using the same methods (longline or recreational gears) in different sub-areas of the model region may be proxies for spatial structuring of the striped marlin population by size. The selectivities at age for the longline fisheries were estimated using a cubic spline parameterisation. Each selectivity function was parameterised with four nodes allowing considerable flexibility in the functional form while minimizing the number of parameters required to be estimated.

Limited length frequency data were available for a number of fisheries and the selectivities for these fisheries were assumed to be equivalent to other fisheries of the same method operating within the same sub-area. Specifically, the aggregate longline fisheries in each sub-area: Other LL1 – 4, (i.e. fisheries 11–14) were assumed to have equivalent selectivities to the corresponding Japanese longline fisheries operating within each sub-area (LL JP1 – 4). No size data were available from the LL TW 4 fishery and the selectivity was assumed to be equivalent to the LL JP4 and Other LL4 fisheries, although limited size data were available from either fishery. Separate selectivities were estimated for the two Australian longline fisheries, the Australian recreational fishery, and the selectivity of the New Zealand longline fishery was assumed the same as the Australian longline fishery in sub-area 2.

For the two recreational fisheries, separate selectivities were estimated, and were assumed to increase with age and remain at full selectivity once attained, i.e a logistic function. This assumption was considered reasonable given the substantially larger fish in the catch size compositions of the recreational fisheries.

The combined effects of assumptions for fishery-specific selectivities and the chosen standardized CPUE included in the model fit were explored in a range of sensitivity models and are described later in the results section. This analysis underpinned the selectivity assumptions made for the reference case model. A sensitivity model was included in the set of key model runs that assumed a logistic (non-decreasing) function for the LL JP3 and LL AU3 fisheries.

4.6. Catchability

Catchability was assumed to be constant over time for the fishery to which the model was being fitted to a standardized CPUE time series. This was because the CPUE is considered informative of temporal trends in population relative abundance. In this case fishing effort has been standardised to account for systematic trends in catchability associated with temporal and spatial changes in the distribution of fishing effort and changes in gear configuration. While it is considered unlikely that such a statistical approach can account fully for systematic variation in catchability over time, the resulting standardised effort series (Figure) represent the best available indices of relative abundance for the stock.

Catchability for all other fisheries not having standardized effort, or having CPUE but not being fitted by the model, was allowed to vary slowly over time (akin to a random walk) using a structural time-series approach. Random walk steps were taken biennially, and the deviations constrained by a prior distribution of mean zero and a variance equivalent to a CV of 0.1. Seasonal variation in catchability was also allowed to explain the strong seasonal variability in CPUE for most of the fisheries.

4.7. Effort variability

Effort deviations, constrained by prior distributions of zero mean and a specified variance, were used to model the random variation in the effort–fishing mortality relation. For all fisheries, a relatively weak penalty was applied to the effort deviations (CV of about 0.7) to reflect the uncertainty in the effort data. For the fisheries to which the model was fitted to standardized effort, the time-variant precision estimates (Figure 7) were applied multiplicatively to the penalties, i.e. as temporal effort deviate penalties that are higher for more precise effort indices.

4.8. Initial population

The population age structure in the initial time period in the region was assumed to be in equilibrium and determined as a function of the average total mortality during the first five years. This assumption avoids having to treat the initial age structure as independent parameters in the model, which is generally poorly determined.

4.9. Parameter estimation

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

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

4.10. Stock assessment interpretation methods

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

4.10.1 Fishery impact

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

We approach this problem by computing biomass time series (at the region level) using the estimated model parameters, but assuming 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 $B_t/B_{t_{F=0}}$ can be interpreted as an index of fishery depletion. The computation of unexploited biomass includes an adjustment in recruitment to acknowledge the possibility of reduction of recruitment in exploited populations through stock-recruitment effects.

4.10.2 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 ($fmult$), the natural mortality (M), the mean weight-at-age (w_a) and the SRR parameters (α and β). All of these parameters, apart from $fmult$ which is arbitrarily specified over a range of 0–50 in increments of 0.1, are available from the parameter estimates of the model. The maximum yield with respect to $fmult$ can easily be determined and is equivalent to the MSY. Similarly the total and adult biomass at MSY can also be determined. The equilibrium yield estimate includes a log-normal bias correction for the assumed distribution of recruitment deviates about the stock-recruitment relationship. The ratios of the current (or recent average) levels of fishing mortality and biomass to their respective levels at MSY are of management interest as limit reference points.

5. Model runs

5.1. Developments from the 2006 assessment

A number of model developments were made starting from the 2006 “base case” assessment model (Table 5). Aside from updating the input data (catch, effort, size frequencies, and standardised CPUE derived from aggregate data), there are nine main differences in the input data and structural assumptions for the reference case model in the current assessment compared to the 2006 assessment (bcase06).

- i. Fixing the steepness parameter (h) of the SRR at 0.8 in the reference case rather than estimating this parameter.
- ii. Incorporation of CPUE indices derived from operational catch and effort data from the recreational fisheries of Australia and New Zealand (sub-area 3).
- iii. Applying temporally varying relative weight on the individual standardised effort indices for the longline and recreational effort time series.
- iv. Applying new biological parameters for growth, maturity-at-age, and the relationship between length and weight.
- v. Including weight-frequency data from the Australian recreational fishery
- vi. Estimating separate selectivity functions for the LL AU3 and REC AU3 fisheries
- vii. Estimating spline selectivity functions for all fisheries besides the REC AU3 and REC NZ3 fisheries for which logistic functions were estimated.
- viii. Revising the assumptions for statistical weighting on the effort deviations and model fit to size data.
- ix. Selecting a single CPUE index from the set of nine available series to which the model was fitted.

For comparison to the 2006 stock assessment, a step-wise sequence of models was formulated that modified the 2006 base-case model to sequentially incorporate each of the changes identified above (Table 5). The sequence of models firstly repeated the bcase06 model estimate using the latest release version of MULTIFAN-CL (1.1.4.2), then updated the model period of the 2006 assessment from 1952-2003 to 1952-2011, and then implemented the developments in a step-wise manner towards a reference case model (Ref.case) against which all models in the current assessment would be compared.

As part of developing the Ref.case, a set of exploratory runs were undertaken that examined model sensitivity to the combined effects of the assumptions for fishery-specific selectivity functions and the CPUE indices to which the model was fitted. Three alternative selectivity functions were considered (Table 6):

- **Sel_log_JP2** – similar to that of **bcase06** with logistic functions for all fisheries except those in sub-areas 1 and 4 (LL JP1, LL Other1, LL JP4, LL Other4, LL TW4) for which spline functions were estimated (four nodes).
- **Sel_JP_AU_3log** – using the assumption for **Sel_log_JP2** but replacing the logistic functions in fisheries: LL JP2, LL Other2, LL AU2 and LL NZ3, with cubic splines.
- **Ref.case** – using the assumption for **Sel_JP_AU_3log** but replacing the logistic functions in fisheries: LL JP3, LL Other3, and LL AU3, with cubic splines.

Likelihood profiles were calculated with respect to the total population scaling parameter, “Totpop”, to determine the impacts of the three selectivity assumptions upon model estimates of absolute abundance while fitting to the standardized CPUE index for the LL JP2 fishery only. Also, for each of the Sel_JP_AU_3log and Ref.case selectivity assumptions, a grid of 10 model runs were fitted to alternative standardized CPUE time series and the absolute biomass estimates compared. The results of these exploratory runs informed the choice of selectivity assumption and which CPUE index was applied for the Ref.case model.

5.2. Sensitivity analyses

Analyses were undertaken to test the Ref.case model sensitivity to: assumptions for the functional form of fishery-specific selectivity; the standardized CPUE time series to which the model was fitted; the growth rate; natural mortality; stock-recruitment relationship steepness; and, the relative weight of the size-frequency data in the model fit (Table 5).

5.2.1 Selectivity function

Given the model uncertainty identified from the exploratory runs, assessing sensitivity to the assumed selectivity function of the LL JP3 and LL AU3 fisheries was considered important (**sel_JP_AU_3log**). In this case a logistic function (non-decreasing with age) was estimated.

5.2.2 CPUE indices

The standardized CPUE for the LL JP2 fishery was used in fitting the Ref.case model. Model sensitivity to alternative indices, or combinations of alternative indices was examined in a set of ten sensitivity runs listed in Table 5. Of these sensitivity runs, three were identified as key model runs: **CP_JP1**, **CP_JP3** and **CP_JP2_AU_2_3**.

5.2.3 Growth

The assumed form of the growth function for the 2006 assessment was repeated as a sensitivity run (**Growth_est**) in which the von Bertalanffy growth coefficient k is fixed at 0.6 and the mean lengths of the first and last age classes were estimated.

5.2.4 Natural mortality

The sensitivity runs applied in the 2006 assessment were repeated with assumed $M = 0.2$ and 0.6 (**M0.2**, **M0.6**).

5.2.5 Steepness

Fixed values of 0.65 and 0.95 were tested (**h0.65**, **h0.95**)

5.2.6 Relative weight of size data

Low relative weight was assumed for length- and weight-frequency data (**Sz_data_wt**). The relative influence of these data was reduced by assigning an effective sample size 0.025 and 0.05 times (respectively) the individual samples, with a maximum sample size of 100.

The ten sensitivity runs in bold above were taken as the key model runs for examining the effects of the primary sources of uncertainty on management reference points in the current assessment.

5.3. Structural uncertainty

An examination of uncertainty in the model structure was integrated into a single analysis that explored the interactions of the assumptions tested in the one-off sensitivity runs, i.e. for the key model runs (Table 5). These interactions were tested in a grid of 288 combinations of the following options for each sensitivity factor.

Factor	Option 1 (Ref.case)	Option 2	Option 3	Option 4
Selectivity	Splines for all LL fisheries	Logistic function for LL JP3 and LL AU3 (JP_AU_2_3)		
Steepness	0.8	0.65 (M0.65)	0.95 (M0.95)	

CPUE	LL JP2	LL JP1 (CP_JP1)	LL JP3 (CP_JP3)	Combination: LL JP2, LL AU2, LL AU3 (CP_JP2_AU_2_3)
M	0.4	0.2 (M0.2)	0.6 (M0.2)	
Growth	Fixed Kopf	Fix k=0.6; estimate length at age 1 and age 10 years (Growth_est)		
Sz_data_wt	Moderate relative weight	Low relative weight (Sz_data_wt)		

A separate model was run for each combination in the grid. The model results were screened to ensure model convergence and reasonable values of key parameters. The criteria for excluding grid runs were if no convergence was achieved and if absolute biomass exceeded 10^6 mt. Runs satisfying these criteria generally produced implausibly high biomass (often in excess of 10^8 mt) and with no relative declines from the initial biomass level. A striped marlin population of a similar magnitude to the bigeye or yellow-fin tuna populations was considered realistically implausible, and given that the CPUE indices for the main longline fisheries indicated at least 50% relative declines, it appeared reasonable to exclude these runs. The percent of grid runs in having these criteria was 21%. A non-parametric bootstrap of the grid results ($n = 5000$) was undertaken that generated a distribution for each management quantity, from which the median and 90%iles were reported.

6. Results

6.1. Stepwise developments from bcase06

In order to examine the impacts of the stepwise developments from the 2006 striped marlin assessment (bcase06) to the Ref.case, the total biomass trajectory of each run is provided in Figure 10.

Re-estimating the bcase06 using the updated version of MULTIFAN-CL (1.1.4.2) (**bcase06_newMFCL**) resulted in a 7% decrease in initial biomass with no change to the trend (Figure 10). Numerous developments and fixes to the software over the past six years may account for this difference, but it most likely relates to a change in the parameterisation for the total population scaling parameter, “Totpop”. The re-estimated model achieved a substantially better fit to the data used for the 2006 assessment, thus being an improvement.

The 41% decline in initial biomass of the updated model (**Update**) can be attributed to the revised (lower) estimates of the Japanese longline catch history (Figure 5). Updating the Australian longline CPUE indices had little impact on the model estimates (**AU_CPUE**) and including the CPUE indices for the recreational fisheries (**NZ_AU_recrcPUE**) increased the current biomass by 27% due to the different trends relative to the longline fishery CPUE indices (Figure 6). Adding temporal effort deviate penalties in fitting to the standardised CPUE indices (**CPUE_temporal**) increased the current biomass on average (39%) and changed but also reduced the declining trend since 1960 (Figure 10). This result most likely reflects the lower relative weight of indices early in the time series having lower precision but also indicate steep relative declines.

As can be expected, fixing steepness at 0.8 (**Steepness_0.8**) has no effect on absolute biomass but did alter the equilibrium model estimates. Applying the new biological parameters altered model estimates for a number of key parameters, in particular reducing the age of maximum fishery selectivity and reducing average recruitments, as the somatic growth component of stock productivity was increased due to the new, faster growth rate. The overall effect was to reduce current biomass by around 26% with a steeper biomass decline in the first 15 years (Figure 10). Adding size data for the REC AU3 fishery (**AU_recSzdata**) and estimating a separate logistic selectivity function for this fishery reduced the

overall biomass by around 11%, but with no change to the trend. Removing potential outliers for the period pre-1986 from these new size data had little effect on the biomass (**AU_rec_sz_post85**).

Estimating a separate logistic selectivity function for the LL AU3 fishery had almost no effect on the absolute biomass (**AU3_selest**) most likely because the model estimate was dominated by the simultaneous fit to the conflicting standardised CPUE time series, and logistic functions were being assumed for all longline fisheries (Figure 10). Replacing the assumption for logistic functions with splines for the selectivities of fisheries LL JP1, 2 & 4, LL Other1,2, & 4, LL TW4, LL AU2 and LL NZ3 (**Sel_splines**) produced a 50% increase in initial biomass and a 100% increase in current biomass (Figure 10). While being a more intuitively satisfying assumption given the difference in size compositions of the longline fisheries relative to the recreational fisheries, this change also significantly improved the model fit to the size data. The next stepwise change applied statistical assumptions for the relative weighting within and among CPUE and size data that are consistent with those of the tuna stock assessments (e.g. bigeye, Davies et al. 2011), (**CP_SZ_wtng**). This moderated the declining biomass trend in the first 15 years of the model period with little effect on the remaining period (Figure 10).

The next stepwise development was to fit the model to only one standardised CPUE index – that of the longline fishery LL JP2 (**CP_JP2_matur**). This decision was based upon both the outcome of the exploratory analyses and a consideration of best practice when abundance indices are conflicting. A description of this selection and the ultimate assumptions for the Ref.case are provided in section 6.2. While having no effect on initial biomass, this change produced a 50% decrease in current biomass estimates with a steady decline estimated for the first 15 years of the model period (Figure 10). Estimating spline function selectivities for the fisheries LL JP3, LL Other3, and LL AU3 in the reference case model (**Ref.case**), only moderately increased biomass with no substantial change to the trend (Figure 10).

In summary, substantial developments were made in advancing from the bcase06 to the Ref.case model in terms of input data, statistical and structural assumptions, resulting in a 32% decrease in estimates of initial biomass, and a 23% decrease in current biomass. Much of this change may be attributed to the 50% downward adjustment to the Japanese longline catch history (Figure 5). Despite the changes to the model assumptions and parameterisation, the general trend in biomass is largely similar to that of the 2006 assessment model, bcase06.

6.2. Exploratory runs

A set of 10 runs were undertaken for each of two selectivity assumptions: Sel_JP_AU_3log and Ref.case, (*see* Table 6 for the definitions), being a series of fits to one, or combinations of, the nine standardized CPUE indices available. Comparisons of the absolute biomass trajectories for these runs are presented for the Sel_JP_AU_3log assumption in Figure 11a, and for the Ref.case assumption in Figure 11b.

Results from the exploratory runs illustrate two features of model uncertainty:

- uncertainty in absolute abundance estimates depending upon the selectivity assumption, and
- differences in the estimated biomass trend depending upon which CPUE index is included in the model fit.

The first feature is evident in the estimated range of initial absolute biomass being substantially larger (20,000 to 100,000 mt) for the Ref.case runs (Figure 11b) compared to that of the Sel_JP_AU_3log runs (18,000 to 30,000 mt, Figure 11a). This indicates higher uncertainty in absolute abundance when spline selectivity functions were estimated for all longline fisheries. The narrower range, and lower estimates of absolute biomass obtained when assuming logistic selectivity functions for the longline fisheries in sub-area 3, is most likely attributable to the constraining effect of the asymptotic selectivity on fishing mortality when fitting to the size data. Higher fishing mortality improves the model fit and results in lower biomass. The spline selectivity function allows for lower fishing mortality and an improved fit to the size data, but contributes greater uncertainty in absolute abundance. Assuming logistic selectivity limits the range of fishing mortality estimates, and most likely masks underlying model uncertainty.

This feature is illustrated further in the likelihood profiles with respect to the parameter "total population scalar, Totpop", for the selectivity assumption of the bcase06 model: Sel_log_JP2 (logistic functions for most fisheries, Table 6); and the Sel_JP_AU_3log and Ref.case selectivity assumptions (Figure 12). A significant and large improvement in the objective function was obtained by estimating spline functions for the Sel_JP_AU_3log assumption, largely due to consistently better fits to size data. Estimating spline functions for all fisheries (Ref.case assumption) resulted in a moderate improvement in the total objective function value but significantly reduced contrast in the profile, suggesting the information available for estimating absolute abundance was reduced.

In respect to the second feature, model estimates of the trend in absolute biomass were sensitive to which of the standardized CPUE indices were included in the fit. This was the case for both selectivity assumptions examined (Figures 11a and 11b). This reflects the conflicting trends in the nine CPUE indices (Figure 6), which results in predictions for biomass declines since 1998 for those models fitted to Japanese and Australian longline and New Zealand recreational indices, while increases or flat trends over the same period are predicted for models fitted to the Taiwanese and Australian recreational indices.

The sensitivity of the model estimates to trends in relative abundance was most likely due to conflicts among CPUE and size data. This was apparent from pairwise comparisons of the size data term of the objective function for models fitted to alternative CPUE indices. Improvement in the fits to the associated size data occurred for some fisheries when other conflicting indices were removed. For example, worse fits to the LL JP1 & 4 weight frequencies, and the LL TW4 length-frequencies were obtained when the LL TW4 CPUE indices were included in the model fit. The fit to the REC NZ3 weight-frequencies was sensitive to the CPUE indices included in the fit - with improvements when LL JP2 & 3 were fit, but also to a lesser extent when the TW 4 indices were included. This indicates conflicts among CPUE and size data both within and among fisheries. For example, since the late-1990s the median weight in the LL AU2 fishery was generally increasing, and also in the most recent period in the LL AU3 fishery (Figure 9), whereas the CPUE indices for both fisheries suggest steady declines (Figure 6). Similar CPUE declines over the same period are apparent for the LL JP2 & 3 and REC NZ3 fisheries, whereas steady declines in median weight have occurred in the REC NZ3 fishery, and increasing median weight has occurred in the AUrec 3 fishery (Figure 9). The relative effect of these conflicts will depend upon which CPUE index is included in the model fit, and this prompted the consideration of this source of model uncertainty in both the sensitivity and structural uncertainty analyses.

6.3. Reference case model selection

In selecting a reference case model the approach followed was for an ideal that: demonstrates the best possible fit to the observations; and, provides an approximate "mid-point" of reference in the range of plausible models against which sensitivity to the primary assumptions may be assessed.

For achieving the first ideal it was necessary to remove sources of conflict among the CPUE indices because it was clear there are differences in trends among the nine available. In situations where multiple indices of abundance are available and conflicting, "a single assessment using all data sets is likely to be wrong, no matter which of the data sets turns out to be unrepresentative" (Francis 2011). Furthermore, indices "that are believed to be unrepresentative should be discarded; they certainly should not be retained and downweighted" (Francis 2011). Accordingly, the available indices were considered in respect of how representative they were of the population. Three factors suggest the LL JP2 fishery provides a representative index of relative abundance of the population:

- being the single largest fishery responsible for 39% of total historical removals and extends through the full extent of the model time period;
- most likely has reasonably consistent operational factors throughout the time period; and,
- operates in the core area of the stock distribution (sub-area 2, Figure 2) with an estimated selectivity over a wide range of recruited age-classes.

In support of this selection, the overlapping period with the other core commercial fisheries, LL AU2 & 3, the trends appear to be reasonably consistent showing a downward trend since the mid- to late-1990s (Figure 6). In contrast, trends of the LL TW4, REC NZ3 and REC AU3 series are inconsistent.

The model fit to the size data over the alternative selectivity assumptions was compared and change in the total objective function noted, which indicated a substantially better fit to the size data was achieved by the Ref.case selectivity assumption.

In respect of the second ideal, the Ref.case selectivity assumption was not characterized by the constraining effects on fishing mortality attributable to the logistic functions in the Sel_JP_AU_3log assumption.

6.4. Fit diagnostics

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

- Overall, there is a very good fit to the observed catch from all fisheries by the model (Figure 13). The log total catch residuals by fishery are shown in Figure 14. The residuals are all relatively small and, for the key longline fisheries (LL JAP1, LL JAP3, LL AU2 & 3 and LL TW4) generally show even distributions about zero. However, a number of other fisheries reveal some temporal trends in the catch residuals, most notably the LL JAP 2 and the LL NZ3 fisheries (Figure 13). These trends indicate a level of systematic lack of fit to the catch data for these fisheries; however, the differences are slight.
- The overall consistency of the model with the observed effort data can be examined in plots of effort deviations against time for each fishery (Figure 15). If the model is coherent with the effort data, we would expect an even scatter of effort deviations about zero. On the other hand, if there was an obvious trend in the effort deviations with time, this may indicate that a trend in catchability had occurred and that this had not been sufficiently captured by the model. For the key longline fisheries, and in particular the LL JP2 fishery providing the standardized effort, the effort deviations are relatively small and there is no evidence of a strong temporal trend in the effort deviations. This indicates that the catch and effort data from these fisheries are consistent with the estimated trends in the vulnerable biomass for the fishery. This is evident when comparing the observed and predicted CPUE from each fishery (Figure 16). While there is considerable variability in CPUE over the time-series, the general trend is consistent with the predictions for each of the key fisheries (LL JAP2, LL JAP3, LL TW4, LL AU2 & 3).
- The increasing trends in the effort deviations from the early periods of the LL AU 2 & 3 fisheries, and also for the REC AU3 and REC NZ3 fisheries (Figure 15) can be ignored because standardized effort data were not available for this period of the fishery. For the periods where effort was supplied to the model, the deviations appear to be distributed evenly about zero.
- For the New Zealand longline fishery (LL NZ3), some trend in the effort deviations is visible (Figure 15). This is due to the negligible catches of striped marlin that were recorded despite a considerable amount of fishing effort. It has been illegal to land commercial catches of striped marlin in New Zealand since 1987 (Kopf et al. 2005) and, consequently, there is little incentive to accurately report when the species is caught. There may have also been confusion regarding the reporting of the species at the start of the fishery that resulted in the catches being rarely reported.
- A generally poor fit to the observed CPUE was obtained for the REC AU3 and REC NZ3 fisheries (Figure 16). While the REC AU3 recent trend is flat or declining preceded by a sharp initial increase, the model predicts a variable decline with a recent increase. Similarly, the REC NZ3 trend suggests no recent increase.
- Overall, there is generally a good fit to the observed weight frequency data for the main fisheries (LL JAP2 & 3, LL AU2 & 3, REC NZ3) with good correspondence between observed and predicted

median weights (Figure 17). The longline fisheries are generally characterized by a single size mode comprised of mainly 3-5 year old fish (Figure 3). The model was unable to fit to the weight frequencies of the LL JP1 and REC AU3 fisheries. In the case of the latter, a steady increase in median weight has been observed which conflicts with the general downward trend in other fisheries and which the model predicts. A low number of observations were available for the LL JP1 fishery relative to others (Table 2), with small fish being sampled in some years, at the lower range for 1 year-old fish. Despite predicting a low median weight, the model was on average positively biased relative to the observations. It is possible this indicates process error in the model's capability of predicting pre-recruit size compositions, and this warrants attention in future assessments.

- Limited length frequency data were available for inclusion in the model, mainly from the domestic longline fisheries in sub-areas 1 and 2 (LL Other1 & 2) and LL JP1–3 fisheries (Table 2). There was a good fit to the aggregated length data from fisheries LL JP2 & 3, suggesting these data are consistent with the associated weight-frequency data (Figure 18). However, the fit was poor for the LL Other1 & 2 fisheries, with the model predictions being positively biased. The fit to these data was somewhat constrained by the assumption that the fisheries' selectivity were grouped with the corresponding Japanese longline fishery in the same sub-area. The poor fit to the LL Other fisheries size data suggests this assumption for equivalent selectivity may be invalid.
- The good fit to the weight frequency data for the LL JP2 & 3, LL AU 3 and REC NZ3 fisheries is reflected in the residual plots with a reasonably even spread of positive and negative residuals over the observed weight range (Figure 19). A concentration of positive residuals in the middle of the range is evident in the fit to the LL AU2 and REC AU2 fisheries, which indicates the model predictions are broad relative to observed modes shown by the wide extent of negative residuals. While the conflicting trend in median weight for the REC AU3 fishery may account for the poor model fit to those observations, the cause of the pattern in residuals for the fit to the LL AU2 fishery data is less obvious. The observed distributions appear to be highly variable with numbers of exceptionally large fish appearing in some years, causing a scatter of positive residuals in the large weight classes (Figure 19). The model is unable to fit these observations while simultaneously fitting the central mode for which positive residuals also occur. Although achieving a reasonable fit to the median weights (Figure 17), perhaps a more complex selectivity function is necessary to characterize this fishery. For example, one with seasonal variation because annual spawning occurs in this sub-area.

6.5. Model parameter estimates

6.5.1 Catchability

The annual catchability for the Japanese longline fishery in sub-area 2 (LL JAP2) was held constant (although allowed to vary seasonally) over the entire period of the model because the model was fitted to the standardized CPUE indices for this fishery, (Figure 20). Among the fisheries, the highest catchability was sustained in sub-area 2 — consistent with the higher catch rates of striped marlin reported from the Coral Sea. However, since the 1980s, high catchability was estimated for the LL Other1 fishery, most likely attributable to the high Korean catch rates.

Catchability was allowed to vary temporally for all other fisheries. The model estimated catchability in the Australian longline fisheries (LL AU2 & 3) to have remained reasonably constant. Despite the attempts to standardise the effort series using the GLM approach, catchability for the Australian recreational fishery in the same sub-area (REC AU3) was estimated to have increased (Figure 20). Similarly, for the New Zealand recreational fishery, catchability is estimated to have steadily increased over the history of the fishery. As noted above, effort data from these recreational fisheries were not available prior to 1994 and 1975 (respectively) and the catchability trend prior to that year is simply the model's attempt to fit the observed catch given a nominal level of effort. For the latter period, catchability is estimated to have increased to the mid 2000s and stabilized (Figure 20).

The four composite ('Other') longline fisheries all display strong trends in catchability over time. These fisheries are comprised of a range of different fisheries and changes in catchability may simply represent a change in the makeup of these fisheries, including the development of new domestic longline fisheries and/or changes in the area of operation and targeting practises of different fleets. A clear example is the increase in estimated catchability in the LL Other1 fishery which corresponds with the increased catches in the Korean fishery since the mid-1970s (Figure 4).

Comparisons of the estimated catchability trends reflect the conflict among the CPUE indices. While the LL JP 2 catchability is held constant, time series deviations are estimated for all other fisheries. Differences among the estimated time series are clear with increasing catchability in recent years estimated for LL JP1, LL TW4, REC AU 3 and REC NZ 3 which indicates these CPUE indices have increasing trends that conflict with the declining trends of the LL JP 2 index. The relatively flat estimated time series catchability for the LL AU 2 and LL AU 3 fisheries suggests a level of consistency with the trend of the LL JP 2 index for the overlapping period.

Strong seasonal trends in catchability are evident from most fisheries. In general, catchability of the longline fisheries was highest in sub-area 2 during the third and fourth quarters and highest in sub-area 3 in the fourth and first quarters. The magnitude of the seasonal variability in catchability increased with increasing (southern) latitude.

6.5.2 Selectivity

An immediate feature of the estimated selectivity functions is the young age at which fish become vulnerable to the fisheries relative to the 2006 assessment, which is due to the faster growth rate assumed for this assessment. Striped marlin become vulnerable to the main longline fisheries in sub-areas 2 and 3 (LL JP2 & 3, LL AU2 & 3, and LL NZ3) from about 2 years of age and are fully recruited by age 3-4 years (Figure 21). Younger fish are vulnerable to the longline fisheries operating in the northern sub-area (LL JP1 and LL Other1), where juvenile fish are present in catches (Figure 3). Although a spline function was assumed for fisheries in sub-areas 1 and 4, asymptotic selectivity was estimated most likely because of the broad size range in catches.

Relatively higher selectivity at older ages were estimated for the longline fisheries in sub-area 3 compared to those in sub-area 2 (Figure 21), reflecting the larger size composition in catches. Selectivity estimates for the LL JP3 and LL AU3 fisheries were remarkably similar.

The logistic functions estimated for the Australian and New Zealand recreational fisheries were similar with somewhat higher selectivity for young fish in the Australian fishery (Figure 21). Both fisheries principally catch large, old fish (4 years and older).

6.5.3 Growth

The fixed growth curve assumed for the Ref.case is shown in Figure 22. Growth rates are high during the first 4 years at which age fish achieve an EFL of nearly 200 cm. Variability in mean length-at-age is high with considerable overlap in the distributions for the fully recruited age classes, 3-4 years.

The Ref.case growth rate is compared to that estimated for the 2006 assessment model (bcase06) and that estimated in the sensitivity model, Growth_est, in Figure 23. Mean lengths-at-age for the first four years are substantially different between the Ref.case and bcase06 growth functions, with a 1 year-old fish being twice the length of that estimated in 2006. However, there is consistency in the asymptotic lengths and this may reflect the common logistic selectivity assumption for the REC NZ3 fishery in both models, and that observations for growth estimation of the large fish were derived from this fishery (Kopf et al. 2009). The mean lengths-at-age estimated for the first and last age classes in the Growth_est model are substantially different to those estimated in 2006 (Figure 23), being higher and lower respectively.

6.6. Stock assessment results

This section principally documents the results of the Ref.case model run, but makes reference to the sensitivity runs (Table 5). The focus of the results on the Ref.case model run does not imply a specific preference for this option, but rather, it serves as a point of reference for the range of uncertainty indicated by the sensitivity model options considered. Symbols used in the following discussion are defined in Table 7 and the key results are provided in Table 8.

6.6.1 Recruitment

There is considerable temporal variation in recruitment over the model period (Figure 24). As was described for the 2006 assessment model (Langley et al. 2006), annual recruitment is estimated to have been high prior to 1971 (33% greater than the mean recruitment) and fluctuated about a lower level (85% of the mean) for the subsequent period. From 1980 onwards, recruitment has fluctuated on approximately a 5-yearly cycle. The recruitment estimates have broad confidence intervals indicating substantial uncertainty, particularly during the early period (1950s and 1960s) (Figure 24), prior to the availability of size data.

There are very limited size data from the early period of the fishery; only New Zealand recreational (REC NZ3) size data were available prior to 1970 (*see* Figure 8). Catch rates from the main Japanese longline fisheries (LL JP2&3) declined rapidly during this period (Figure), while relatively high catches were taken (Figure 1). The model is accounting for this initial decline in CPUE, in part, by a decline in recruitment from 1950 to 1970. In the absence of size data from the key longline fisheries, the model estimates of recruitment for this period should be interpreted with some caution. On account of this feature, the sensitivity model **msy_recent** expresses equilibrium yield quantities using only recruitment estimates since 1971, as this may best represent current recruitment, and hence, current productivity levels (Table 8).

6.6.2 Biomass

The annual trends in total and adult biomass are consistent with the temporal trend in recruitment described in the previous section. Biomass was estimated to be high during the 1950s and declined sharply until the late 1960s (Figure 25). Since the early 1970s, biomass is predicted to have declined steadily towards a level below that which supports the *MSY*, with a recent increase since 2004. There is a high level of uncertainty associated with the annual biomass estimates, particularly for the 1970s and early 1980s. This may be also a result of size data only being available since 1970 for the key longline fisheries.

The sensitivity of model biomass estimates to the assumptions tested in the other key model runs are presented in Figure 26. As previously described, estimates of absolute biomass and the relative trend are highly sensitive to the standardized CPUE time series to which the model is fitted. This affects the absolute initial biomass and, given the CPUE trend, current biomass. For example, the relatively flat trend of the LL JP1 CPUE index, results in model (**CP_JP1**) predictions of current biomass which are over three-times higher than the Ref.case, and a stock status of 70% above the *MSY* level (Table 8). Adding the indices for the LL AU2 & 3 fisheries in the model fit (**CP_JP2_AU_2_3**) results in only a slight change, because these indices are reasonably consistent to those from the LL JP2 fishery.

Estimating logistic selectivity functions for the LL JP3, LL Other3 and LL AU3 fisheries (**sel_JP_AU_3log**) produces and slight decline in biomass with no substantial change to estimates of stock status (Figure 26, Table 8).

Lower and higher values for stock-recruitment steepness (**h0.65**, **h0.95**) have almost no impact on absolute biomass estimates, but substantially change equilibrium biomass estimates, resulting in more pessimistic and optimistic predictions of *MSY*-based estimates of stock status, respectively (Table 8). In contrast, lower and higher assumed values for natural mortality affect both absolute and equilibrium biomass estimates, resulting in lower and higher absolute biomass, and substantially more pessimistic and optimistic stock status, respectively (Figure 26, Table 8).

Absolute biomass estimates increase by around 10-20% when the growth rate is estimated (**Growth_est**) or the relative influence of size data on the model fit is down-weighted (**Sz_data_wt**), with a more optimistic stock status predicted (Figure 26, Table 8).

6.6.3 Fishing mortality

Fishing mortality (exploitation) rates for adult striped marlin are estimated to have increased sharply in the mid 1950s (Figure 27) following the development of the Japanese longline fishery in sub-area 2 and the initial period of high catches (*see* Figure 4). Since that time, fishing mortality rates for adult striped marlin have steadily increased to a peak of over 0.6 per annum in 2003, after which they have declined sharply to around 0.4 in the most recent year. Fishing mortality rates for juvenile striped marlin are estimated at a lower level throughout the model period because these fish (< 3 years-old) are generally not fully recruited to the main longline fisheries (Figures 3 and 21), although they have slowly increased through time, perhaps as a result of the development of distant water and domestic longline fisheries by PICTs in the equatorial sub-area of the model.

6.6.4 Fishery impact

An indicator of the impact of fishing on the stock is to compare the biomass trajectories with fishing and the predicted biomass trajectory in the absence of fishing. The impact can be expressed as a proportional reduction in biomass ($1 - B_t / B_{0t}$) and calculated for different components of the stock: juvenile, adult, and the proportion of the stock vulnerable to the main longline fisheries. It is possible to ascribe the fishery impact to specific fishery components in order to see which types of fishing activity have the largest impact on the total biomass and spawning potential (Figure 28).

The model indicates that the entire fishery has had a substantial impact on the levels of total and spawning biomass (Figure 28), with current levels being 46% and 34% of that which would have occurred in the absence of fishing (Table 8). The impact of the entire fishery is estimated to have increased sharply in the late 1990s with a recent decline since 2005. Whereas the most sustained and substantial impacts have been due to the Japanese longline fishery, these have declined since the early 1990s, to be replaced primarily by the impacts of the Australian fisheries and the LL Other fisheries in sub-areas 1 and 4. Components of the Other1_4 impacts include the Korean fishery in sub-area 1 that expanded since the mid-1970s but catches in this fishery have recently declined (Figure 4), and more recently the Taiwanese, Chinese and to some extent the expanding PICT fisheries. The fishery impacts are low for the recreational fisheries.

6.6.5 Yield analysis

The yield analyses conducted in this assessment incorporate the SRR (Figure 29) into the equilibrium biomass and yield computations. The Ref.case model steepness coefficient of the SRR was assumed to be 0.8, considerably higher than that estimated for the 2006 assessment (0.51).

Equilibrium yield and total biomass as functions of multiples of the 2007–2010 average fishing mortality-at-age (f_{mult}) are shown in Figure 30. Yield is maximized at $f_{mult} = 1.24$ for an MSY of 2,081 t per annum, similar to the average annual catch from the model region since 1984 (Figure 1). This implies that the ratio $F_{current} / \tilde{F}_{MSY}$ is 0.81. The equilibrium total biomass at MSY is estimated at 7331 t, approximately 38% of the equilibrium unexploited biomass (Table 8).

There is a high level of uncertainty regarding the natural mortality of striped marlin. The sensitivity of the model to the assumed value of natural mortality (Ref.case $M=0.4$, for all age classes) was investigated by comparing separate analyses using an extremely low value for M (0.2) and a higher value (0.6). The Ref.case model equilibrium yield, fishing mortality and biomass estimates were most sensitive to this source of uncertainty, with an $F_{current} / \tilde{F}_{MSY}$ ratio of 2.21 and 0.30, and $SB_{current} / SB_{MSY}$ of 0.37

and 1.34, for the **M0.2** and **M0.6** models respectively (Table 8, Figure 31). To a lesser extent, equilibrium yield estimates were sensitive to the steepness parameter, with $SB_{current}/SB_{MSY}$ of 0.67 and 1.14, for the **h0.65** and **h0.95** models respectively.

Estimating the growth parameters for striped marlin resulted in slower growth estimates, higher absolute recruitments and selectivity functions having asymptotes at higher ages, (**Growth_est**). The combined effects on equilibrium yield estimates was for higher yield and SB_{MSY} , with a more optimistic estimate of stock status (Table 8).

The relative equilibrium biomass levels that support MSY were not sensitive to the standardized CPUE index to which the model was fitted, e.g. SB_{MSY}/SB_0 was 0.27 and 0.26 for the Ref.case and CP_JP1 runs, respectively. However, given the model's sensitivity of absolute biomass to these input data, estimates of yield and stock status relative to equilibrium biomass were highly sensitive, e.g. for the CP_JP1 run, MSY increased by 53%, and $F_{current}/\tilde{F}_{MSY}$ decreased to 0.25 (Table 8).

The Kobe-plot conveniently displays trends in the status of the stock relative to F_{MSY} , B_{MSY} , and SB_{MSY} reference points over the model period. Trends for total and spawning biomass are provided in Figure 32. The trends of the two are similar, with the spawning biomass values being slightly higher on the biomass axis. Fishing mortality rates were initially very high in the early 1950s, after which they declined in the 1960s, but have increased steadily since 1980, and exceeded F_{MSY} in the early 2000s, but have been below F_{MSY} since 2005. After a rapid decline since the 1950s, total and spawning biomass have declined steadily, and the Ref.case estimates have remained below the B_{MSY} , and SB_{MSY} levels since 2003.

The spawning biomass-based Kobe plots for the Ref.case and for the key model runs (one-off sensitivity runs) are compared in Figure 33. Although the general temporal patterns of the two reference points are similar in respect of increasing fishing mortality and decreasing spawning biomass, the current estimates relative to the B_{MSY} and SB_{MSY} levels differ among the runs reflecting the sensitivity of the model equilibrium yield and biomass estimates to the assumptions tested. Temporal trends and stock status were relatively insensitive to the assumptions for selectivity, the relative weight of the size data in the model fit, and the addition of the standardized CPUE of the LL AU2 & 3 fisheries (Sel_JP_AU_3log, Sz_data_wt, CP_JP2_AU_2_3). Estimating growth parameters resulted in a moderately more optimistic stock status (**Growth_est**). Stock status was substantially more optimistic for runs assuming higher natural mortality, steepness and fitted to the standardized CPUE of the LL JP1 fishery (M0.6, h0.95, and CP_JP1). Substantially more pessimistic stock status was estimated for the runs assuming lower natural mortality and steepness (M0.2 and h0.65). The range for the estimates of current stock status (based upon the period 2007-10) relative to these reference points for the key model runs is presented in Figure 34, which illustrates a high level of uncertainty.

The results from the structural uncertainty analysis (grid) are presented with respect to the status of the stock relative to F_{MSY} and SB_{MSY} reference points in Figures 35 and 36, respectively, for the 229 plausible runs included in the summary. Most notable was the clear separation of the estimates of status relative to the three options assumed for natural mortality, showing little overlap of the Ref.case values when a higher or lower value was assumed. This factor appears to be the dominant source of uncertainty in the estimates of stock status. The second-most important source of uncertainty was the standardized CPUE index included in the model fit. Grid runs fitted using the CP_JP1 option were consistently lower relative to F_{MSY} and higher relative to SB_{MSY} (Figures 35 and 36). The effects of the other grid factors reflected the results of the key model runs and appear less influential on model uncertainty.

In considering the results from the structural uncertainty analysis (grid, Figure 37), the range of grid estimates was extremely broad, with a median value for $SB_{current}/SB_{MSY} = 1.09$, (one standard error range = 0.32 – 2.89) (Table 8). The probability that $SB_{current}$ is below $SB_{current}$ was 50%. The range largely reflects the large amount of uncertainty in these estimates attributable to values for natural mortality and steepness considered in the key model runs. In addition the results for the factor CP_JP1

diverged widely from the Ref.case values, and it is not known whether this CPUE index is representative of population relative abundance. These alternative assumptions result in model estimates substantially and consistently different to the Ref.case. In the hypothetical absence of the key model runs M0.2, M0.6 and CP_JP1, the remaining 7 runs indicate a stock status close to, or below the SB_{MSY} reference point (Figure 36), and with current fishing levels most likely below the F_{MSY} reference point (Figure 35).

The yield analysis can also predict the level of biomass that would result at equilibrium if current levels of fishing mortality continued ($B_{F_{current}}/B_{MSY}$ and $SB_{F_{current}}/SB_{MSY}$). The Ref.case model predicts that the total and spawning biomasses would increase to 112% and 118% of the levels that support MSY , respectively.

6.6.6 Stock assessment conclusions

The main conclusions of the current assessment (based upon the median of the uncertainty grid estimates, and the plausible range of key model runs) are as follows.

1. The decreasing trend in recruitment estimated in the 2006 assessment remains a feature of the current assessment, particularly during the first 20 years. It is concurrent with large declines in catch and CPUE in the Japanese longline fishery in area 2. Recruitment over the latter 40 years of the model period declines slightly.
2. Estimates of absolute biomass were sensitive to assumptions about selectivity and to conflicts among the standardized CPUE time series. The reference case model (Ref.case) estimated selectivity functions that decrease with age for the main longline fisheries that achieved the best fit to the size data. The CPUE time series for the Japanese longline fishery in area 2 was selected for fitting the Ref.case model because this time series was considered to be the most representative of changes in overall population relative abundance. Alternative options for selectivity assumptions and the CPUE time series included in the model fit were explored in sensitivity and structural uncertainty analyses, and are presented as the key model runs.
3. Estimates of equilibrium yield and the associated reference points are highly sensitive to the assumed values of natural mortality and, to a lesser extent, steepness in the stock-recruitment relationship. Estimates of stock status are therefore uncertain with respect to these assumptions.
4. If one considers the recruitment estimates since 1970 to be more plausible and representative of the overall productivity of the striped marlin stock than estimates of earlier recruitments, the results of the ‘msy_recent’ analysis could be used for formulating management advice. Under this productivity assumption MSY was 16% lower than the grid median value, but the general conclusions regarding stock status were similar.
5. Total and spawning biomass are estimated to have declined to at least 50% of their initial levels by 1970, with more gradual declines since then in both total biomass ($B_{current}/B_0=36\%$) and spawning biomass ($SB_{current}/SB_0=29\%$).
6. When the non-equilibrium nature of recent recruitment is taken into account, we can estimate the level of depletion that has occurred. It is estimated that, for the period 2007-2010, spawning potential is at 43% of the level predicted to exist in the absence of fishing, and for 2011 is at 46%.
7. The attribution of depletion to various fisheries or groups of fisheries indicates that the Japanese longline fisheries have impacted the population for the longest period, but this has declined to low levels since 1990. Most of the recent impacts are attributed to the ‘Other’ group of longline fisheries in areas 1 and 4, and to a lesser extent the ‘Other’ and Australian fisheries in areas 2 and 3.
8. Recent catches are 20% below the MSY level of 2182 mt. In contrast, the ‘msy-recent’ analysis calculates MSY to be 1839 mt, which places current catches 5% below this alternative MSY level. **Based on these results, we conclude that current levels of catch are below MSY but are approaching MSY at the recent [low] levels of recruitment estimated for the last four decades.**
9. Fishing mortality for adult and juvenile bigeye tuna is estimated to have increased continuously since the beginning of industrial tuna fishing. Apart from those model runs that assumed lower

natural mortality or steepness, $F_{current}/F_{MSY}$ was estimated to be lower than 1. For the grid median, this ratio is estimated at 0.58. **Based on these results, we conclude that overfishing is not occurring in the striped marlin stock.**

10. The reference points that predict the status of the stock under equilibrium conditions at current F are $B_{F_{current}}/B_{MSY}$ and $SB_{F_{current}}/SB_{MSY}$. The model predicts that at equilibrium the biomass and spawning biomass would increase to 129% and 144%, respectively, of the level that supports MSY. This is equivalent to 39% of virgin spawning biomass. Current stock status compared to these reference points indicates that the current total and spawning biomass are close to the associated MSY levels ($\frac{B_{current}}{B_{MSY}} = 0.96$ and $\frac{SB_{current}}{SB_{MSY}} = 1.09$). The structural uncertainty analysis indicates a 50% probability that $SB_{current} < SB_{MSY}$, and 6 of the 10 key model runs indicate the ratio to be < 1 . **Based on these results above, and the recent trend in spawning biomass, we conclude that striped marlin is approaching an overfished state.**

7. Discussion

This report presents an update of the first assessment of striped marlin in the southwest Pacific Ocean undertaken in 2006. Although we have expanded upon the first assessment in terms of a wider consideration of model uncertainty, results revealed high uncertainty surrounding some of the key parameters included in the assessment model. In particular, assumptions regarding natural mortality and in the selected index of relative abundance to which the model is fitted. However, the estimated uncertainty in the assessment may be exaggerated as the range of values for natural mortality may be too extreme, and one of the indices of relative abundance included in the key model runs was most likely not representative (Japanese longline fishery in sub-area 1, LL JP1). Given lower weight to these key model runs, the range of the stock status estimates for the remaining seven key model runs supports the general conclusions based on median estimates across the uncertainty grid.

This assessment has entailed substantial changes to the input data and a wider range of exploratory model runs with a comprehensive analysis of model uncertainty. A key change to the inputs was a revised total catch time series for the main longline fishery accountable for the largest catch over the model period. The 50% reduction in this catch has resulted in lower absolute biomass estimates and equilibrium yield; however, estimates of stock status (close to the MSY level) have remained similar. The second major change to the assessment has been the revised biological parameters, with substantially higher growth rates. This has lowered the mean age for recruitment to the fisheries and reduced the average absolute recruitment estimates but with increased somatic growth, resulting in a smaller but relatively more productive population. This assessment has included a reasonably thorough consideration of six factors (being both assumptions and inputs) in a series of sensitivity runs and a structural uncertainty analysis (grid).

Despite the updated estimates of stock status being somewhat similar to that of the 2006 assessment, the dominant feature of the updated assessment is the high level of uncertainty in this estimate. These are attributable to mainly two sources: assumed natural mortality and the chosen index of relative abundance. Although the assumed steepness value for the spawning stock-recruitment relationship was also a source of uncertainty, its effect was less than that of the natural mortality assumption.

Since the 2006 assessment, there has been no change in the current understanding of the most appropriate natural mortality value for southwestern Pacific striped marlin – and therefore, the same approach for addressing uncertainty in this parameter was followed. As an indication of the relative impact of this parameter, a 50% decrease or increase of the assumed mortality value (0.2 and 0.6) resulted in the Ref.case value for $F_{current} / F_{MSY}$ increasing by 173% or decreasing by 63%, respectively. As such, it was the dominant effect in the uncertainty grid results. Given the faster growth rate

considered in this assessment, higher or lower values for natural mortality have a relatively greater impact on model estimates.

The second source of uncertainty was the index of relative abundance to be used in fitting the model. For this assessment, nine alternative indices of relative abundance were available, 5 of which spanned all, or most of, the model calculation period. The selection of one index regarded as being most representative of the underlying population trends was made for defining the Ref.case. Conflicts among the indices were clear, and were reflected in the uncertainty in absolute biomass estimates, particularly for runs assuming spline selectivities for all longline fisheries. In the absence of a clear basis for determining which was the most representative index, the approach adopted was to present a range of possible assessments in which unrepresentative indices were omitted (Francis 2011, Schnute & Hilborn, 1993). An outcome of this approach was high uncertainty in estimates of current absolute biomass and current stock status because one CPUE option (CP_JP1) predicted high biomass (Figure 36).

To re-evaluate the large uncertainty indicated in the assessment results, relative weights may be assigned to the key model runs given the various assumptions and hence, reweight the options for the factors included in the structural uncertainty analysis. In particular, it would be important to assign relative weights to the values assumed for natural mortality and the chosen relative abundance indices as these were the two factors that dominated the estimated uncertainty.

Whereas the value for M assumed for the Ref.case model is consistent with that estimated from a meta-analysis of available marlin estimates (Piner & Lee, 2010), the range of sensitivity values evaluated were well beyond the range of the weighted mean obtained ($M = 0.38$ 95%CI ± 0.038). Despite different growth estimates (slower rates) being included in the meta-analysis, the deviation of the sensitivity values used in this assessment from the weighted mean (and any of the values analysed) was large. Therefore, the range considered in this assessment may be determined to be too broad, and consequently, the level of plausible uncertainty indicated due this parameter may be over-estimated. It is recommended that a relatively low level of importance be given to the results of key model runs **M0.2** and **M0.6**. For future striped marlin assessments, a narrower range would be recommended, and reducing uncertainty in this parameter is regarded as a top priority.

The five standardized CPUE indices of relative abundance included in the estimation of model uncertainty indicated by the key model runs : LL JP1, LL JP2, LL JP3, LL AU2 and LL AU3. Evidence for consistency among four of these indices exists in the model estimates of time series catchability and the uncertainty grid results. When constant catchability was assumed for the LL JP2 fishery in the Ref.case model fitted to this fishery's index, generally flat catchabilities were estimated for the periods of overlap of the LL AU2 and LL AU3 fisheries (Figure 20). Apart from the years before 1970 when catches were low, a generally flat catchability time series was also estimated for the LL JP3 fishery. These flat catchability estimates indicate that the model interprets these indices as showing similar trends. In contrast, the estimated catchability trend for the LL JP1 fishery exhibits a steady increase (Figure 20). The uncertainty grid results for $\frac{SB_{current}}{SB_{MSY}}$ using the CPUE option CP_JP1 were consistently higher than the range estimated for the runs using the other four indices (CP_JP2, CP_JP3, CP_JP2_AU_2_3) (Figure 36). This clearly indicates a different trend for this index. Therefore, relative to the other indices, the LL JP1 is much less likely to be representative of changes in relative abundance, and the model runs fitted to this index should be assigned lower relative weight.

Model uncertainty due to the choice of a representative index of relative abundance was an important feature of this assessment, so it is recommended as a high priority that future striped marlin assessments further evaluate each index to provide an empirical basis for excluding those trends deemed unrepresentative.

Simplistic assumptions were made in terms of model structure. These include a single sex dimension and a single model region with the assumption of homogeneous mixing. These are strong assumptions that were necessary given the current level of data available. There is evidence for sexual dimorphism in

the relationships between both age and length, and length and weight, with females tending to be larger than males (Kopf et al 2011). Analyses of observer-sampled sex and size data (unpublished) also show clear spatial patterns. Average sizes progressively increase further south, with the largest fish caught south of 35S. Sizes also increase further west, with some of the smallest fish, on average, caught east of 170E and north of 15S. In addition, more males are caught at sizes below about 260 cm and in areas north of 30S, but females become more common in catches further south and at larger sizes. The apparent conflicts among the input data to the model may reflect this temporal-spatial complexity in the population. An alternative model structure that includes processes implied by these patterns (e.g. sex-specific growth rates and selectivities) may reduce data conflicts.

A large part of the updated assessment included a consideration of age-specific fishing mortalities because the updated growth estimates substantially altered the age-composition of the recruited stock. The faster growth rate meant that 3 year-old fish were fully recruited and formed the bulk of the exploitable size classes for the major fisheries, e.g. the selectivity-at-age of JP2 largely exploiting 3 year olds. Consequently selectivity-at-age estimates were higher for younger age-classes compared to the 2006 estimates, and spline functions performed significantly better in fitting to the size compositions because larger (and older) fish were not abundant in catches from the main longline fisheries. Assumptions for logistic selectivity functions resulted in lower absolute abundance estimates because this improved the fit to size composition data via higher fishing mortality estimates resulting in fewer large (and old) fish. Estimating spline selectivities for these fisheries resulted in higher absolute abundance estimates as the larger (and older) fish “escaped” fishing mortality, aside from the recreational fisheries which clearly captured the largest fish. Assuming decreasing selectivity functions for the longline fisheries was most intuitive given the substantial differences in the size composition relative to the recreational fisheries. However, the option for logistic selectivity for the longline fisheries in area 3 was retained because this performed only marginally worse in fitting the size data. This aspect of the current assessment may be considered an improvement over the assumptions made in the 2006 assessment.

An area of uncertainty not considered in this assessment was that of fishery catch histories. An area which merits attention is the unaccounted for discard mortality of fish tagged and released from the recreational fisheries. Brodziak’s (2012) meta-analysis of post-release mortality of striped marlin based upon PSAT studies estimates a mean mortality rate of 25.4% (95%CI = 12.6 to 44.6%). With 94% of fish being tagged in the Australian fishery since 1997, 57% in the New Zealand fishery since 1990, and average total annual catches of 1178 and 1459 respectively, this would amount to a significant increase in the fishing mortality for these fisheries. This would entail restructuring the model size stratification because the size composition of tagged fish is grouped into 5 kg bins, but this is unlikely to significantly affect overall model results. Including a consideration of this “unseen” mortality in future assessments is recommended.

In summary, the main conclusions of this assessment are somewhat more optimistic than those of the 2006 assessment. However, this assessment suggests higher uncertainty, particularly due to the range of alternative values considered for natural mortality ($M_{0.2}$, $M_{0.6}$) and the alternative CPUE time series (CP_{JP1}) to which the model was fitted. It is argued that these key model runs should be assigned low relative weight, and the remaining seven key model runs provide a more plausible range for considering current stock status (Figures 34-36). This plausible range is consistent with the grid medians indicating biomass to be close to the MSY levels, and fishing mortality to be below that level at which MSY is obtained.

To progress the assessment, it is recommended that further research is conducted in the following areas:

1. Studies to evaluate the most likely values for natural mortality, e.g. dedicated tagging studies, further work on catch-at-age, or meta-analyses of other marlin populations.
2. Fisheries characterisations to identify the fishery most likely to provide a representative index of relative abundance. This would entail more comprehensive analyses of catch and effort data, particularly variations in targeting and fishing power of the Japanese longline fleet to increase the confidence in the application of these data as an index of stock abundance. In addition, fine-

scale analysis of these CPUE data may identify seasonal shifts in areas of relatively high CPUEs which may assist in defining movements of striped marlin in the model region.

3. Age-specific processes may be poorly estimated using the current model structure because of the low range of age classes in longline catches (primarily 3-4 year olds); high variability in mean lengths-at-age; the various conversions required to derive mean weight-at-age; and the fast growth rate having an asymptote at a relatively young age. Mortality-at-age estimates in the model may be improved with the provision of direct age-observations of the population, e.g. catch-at-age data.
4. Given the likely problems in estimating age-related processes, fishing mortality may be better estimated via selectivity functions in respect of length rather than age.
5. Attempts should be made to explicitly describe temporal and spatial processes with respect to numbers at length and sex in the population dynamics model. Further analysis of tagging data similar to that by Chambers et al. (2012) would assist in formulating these dynamic processes.
6. Include in sensitivity analyses the unaccounted discard mortality of fish tagged and released from the recreational fisheries due to post-release mortality.

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Table 1. Description of the fisheries and summary of information used in the assessment.

Fishery	Sub-area	Label	Method	Flag	Catch	Effort	Years
1	1	LL JAP1	Longline	Japan	Number	Hooks	1952–2011
2	2	LL JAP2	Longline	Japan	Number	Hooks	1952–2011
3	3	LL JAP3	Longline	Japan	Number	Hooks	1952–2011
4	4	LL JAP4	Longline	Japan	Number	Hooks	1954–2011
5	4	LL TW4	Longline	Taiwan	Number	Hooks	1967–2011
6	2	LL AU2	Longline	Australia	Number	Hooks	1990–2011
7	3	LL AU3	Longline	Australia	Number	Hooks	1990–2011
8	3	LL NZ3	Longline	New Zealand	Number	Hooks	1993–2011
9	3	REC AU3	Recreational	Australia	Number	Days	1990–2011
10	3	REC NZ3	Recreational	New Zealand	Number	Days	1952–2011
11	1	LL Other1	Longline	Other flags	Number	Hooks	1967–2011
12	2	LL Other2	Longline	Other flags	Number	Hooks	1967–2011
13	3	LL Other3	Longline	Other flags	Number	Hooks	1968–2011
14	4	LL Other4	Longline	Other flags	Number	Hooks	1976–2011

Table 2. Number of striped marlin in length- and weight-frequency samples for each of the defined fisheries.

	Length-frequency	Weight-frequency
LL JAP1	197	1690
LL JAP2	1533	27,922
LL JAP3	1027	12,878
LL JAP4	0	148
LL TW4	83	0
LL AU2	594	39,642
LL AU3	527	9003
LL NZ3	44	0
REC AU3	0	2075
REC NZ3	0	14,702
LL Other1	5210	0
LL Other2	10,894	0
LL Other3	47	0
LL Other4	719	0
Total	20,875	108,060

Table 3. Biological parameters and starting values (in brackets) used in the assessment.

Parameter	Value	Comment	Source
Number of age classes	10	Fixed. Pools all fish 10 years and older together in the oldest age class.	See sources under other parameters.
Length-weight relationship (L = aW ^b)	a= 4.4990 e-07; b= 3.6165	Fixed	Estimated from data supplied for the model region
Growth parameters (von Bertalanffy)	Mean length at age 1: 121 cm; Mean length at age 10+: 221 cm; k: 0.449 year ⁻¹ Sensitivity: k = 0.6 Mean length at age 1 Mean length at age 10+	Fixed Fixed Fixed Fixed Estimated Estimated	Kopf et al. 2009, 2011
Natural mortality	0.4 year ⁻¹ Sensitivity: 0.2, 0.6	Fixed	Boggs 1989; Hinton and Bayliff, 2002.
Maturity ogive (females)	Age: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 Proportion: 0, 0.5, 0.75, 1, 1, 1, 1, 1, 1, 1	Fixed	Skillman and Yong 1976; Kopf pers.comm..
Beverton-Holt stock-recruitment relationship - steepness	0.8 Sensitivity: 0.65, 0.95	Fixed	

Table 4. Main structural assumptions used in the analysis.

Category	Assumption
Observation model for total catch data	Observation errors small, equivalent to a residual SD on the log scale of 0.07.
Observation model for length- and weight-frequency data	Normal probability distribution of frequencies with variance determined by sample size and observed frequency. Effective sample size is assumed to be 0.05 times actual weight-frequency sample size and 0.025 times the actual length-frequency sample size with a maximum effective sample size of 100.
Recruitment	Occurs as discrete events in November of each year. Recruitment is weakly related to spawning biomass with a 1 year lag via a Beverton-Holt SRR with steepness fixed at 0.8. Alternative, values were 0.65 and 0.95.
Initial population	Equilibrium age structure in the region as a function of the estimated natural mortality.
Age and growth	10 annual age-classes, with the last representing a 10+ age group. A fixed von Bertalanffy growth curve was assumed. 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. Parameter values are in Table 3.
Selectivity	Constant over time. Coefficients for particular age-classes above age 6 years are constrained to be equal for particular fisheries. Spline selectivities were assumed for longline fisheries and logistic (non-decreasing with increasing age) were assumed for the recreational fisheries (<i>see</i> Table 6 – Ref.case)
Catchability	Seasonal variation for all fisheries. All fisheries, except that for which the CPUE index is fitted, have structural time-series variation, with random steps (catchability deviations) taken every 2 years. Catchability deviations constrained by a prior distribution with a normal mean 0 and SD 0.1.
Fishing effort	Variability of effort deviations constrained by a prior distribution with mean 0 and SD 0.22 for all fisheries.
Natural mortality	Constant at 0.4 per year for all age classes. Sensitivities 0.2, 0.6.
Movement	Not relevant for the single region model.

Table 5. Summary of the stepwise development model runs undertaken for the 2012 striped marlin assessment leading to the Reference case. Run14 to Run31 are one-off sensitivities to the Reference case, and those in **bold** are key model runs for the assessment.

Run	Name	Description
bcase06	bcase06	2006 base case run: $M=0.4$, uninformative prior on steepness
Run2	bcase06_newMFCL	bcase06 fitted using MULTIFAN-CL version 1.1.4.2
Run3	Update	Run2 + update all data used in 2006.
Run3a	AU_CPUE	Run3 + constant catchability for AU longline CPUE indices; downweight NZ longline fishery effort-deviates.
Run4	NZ_AU_recrcPUE	Run3a + standardised CPUE indices for AU and NZ recreational fisheries; excl. LF outliers in fisheries 1, 14
Run5	CPUE_temporal	Run4 + temporal weighting on standardised effort.
Run6	Steepness_0.8	Run5 + stock recruitment relationship steepness fixed = 0.8.
Run7	New_biology	Run6 + new biological parameters for fixed growth rate.
Run7a	AU_recrcSzdata	Run7 + input new size data and estimate selectivity for AU recreational fishery
Run8	AU_recrcsz_post85	Run7a + remove pre-1986 size composition data for AU recreational fishery
Run9	AU3_selest	Run8 + selectivity estimated for AU3, downweight LF in NZ3.
Run10	Sel_splines	Run9 + estimate splines for fisheries: 1, 11, 2, 12, 4, 14, 5, 6, 8.
Run11	CP_SZ_wtng	Run10 + CPUE uniform $CV=0.2$, downwt size data.
Run12	CP_JP2_matur	Run11 + fit to JP2 CPUE only, new maturity-at-age schedule.
Run13	Ref.case	Run12 + estimate splines for fisheries: 3, 13, and 7.
Run14	sel_JP_AU_3log	Estimate logistic selectivities for fisheries: 3, 13, and 7.
Run15	CP_JP1	Fit to JP1 CPUE only.
Run16	CP_JP3	Fit to JP3 CPUE only.
Run17	CP_JP4	Fit to JP4 CPUE only.
Run18	CP_JP_AU_2	Fit to JP2 and AU2 CPUE.
Run19	CP_JP_AU_3	Fit to JP3 and AU3 CPUE.
Run20	CP_JP2_AU_2_3	Fit to JP2, AU2 and AU3 CPUE.
Run21	CP_TW4	Fit to TW4 CPUE only.
Run22	CP_TW4_NZ_recrc3	Fit to TW4 and NZ3 recreational CPUE.
Run23	CP_TW4_AU_recrc3	Fit to TW4 and AU3 recreational CPUE.
Run24	CP_JP3_NZ_recrc3	Fit to JP3 and NZ3 recreational CPUE.
Run25	h0.65	Assume stock recruitment relationship steepness = 0.65.
Run26	h0.95	Assume stock recruitment relationship steepness = 0.95.
Run27	M0.2	Assume natural mortality = 0.2.
Run28	M0.6	Assume natural mortality = 0.6.
Run29	Growth_est	Fix $k = 0.6$ and estimate lengths at 1 st and last ages
Run30	Sz_data_wt	Downweight size data.
Run31	msy_recent	Stock-recruitment relationship calculated over 1970-2010 for determining equilibrium yield

Table 6. Three alternative assumptions of selectivity functions for the fisheries making up each selectivity group. For each assumption, likelihood profiles were calculated for the total population scaling parameter, Totpop.

Selectivity group	Fishery	Fishery label	Sel_log_JP2	Sel_JP_AU_3log	Ref.case
1	1, 11	JP1, Other1	Cubic-spline	Cubic-spline	Cubic-spline
2	2, 12	JP2, Other2	Logistic	Cubic-spline	Cubic-spline
3	3, 13	JP3, Other3	Logistic	Logistic	Cubic-spline
4	4, 14, 5	JP4, Other4, TW4	Cubic-spline	Cubic-spline	Cubic-spline
5	6, 8	AU 2, NZ 3	Logistic	Cubic-spline	Cubic-spline
6	10	REC NZ3	Logistic	Logistic	Logistic
7	9	REC AU3	Logistic	Logistic	Logistic
8	7	AU3	Logistic	Logistic	Cubic-spline

Table 7. Description of symbols used in describing the stock assessment results and yield analysis.

Symbol	Description
$C_{current}$	Average annual catch over a recent period ³
C_{latest}	Catch in the most recent year
$F_{current}$	Average fishing mortality-at-age ⁴ for a recent period
F_{MSY}	Fishing mortality-at-age producing the maximum sustainable yield (MSY^5)
$Y_{F_{current}}$	Equilibrium yield at $F_{current}$
$Y_{F_{MSY}}$	Equilibrium yield at F_{MSY} . Better known as MSY
$C_{current}/MSY$	Average annual catch over a recent period relative to MSY
C_{latest}/MSY	Catch in the most recent year relative to MSY
F_{mult}	The amount that $F_{current}$ needs to be scaled to obtain F_{MSY}
$F_{current}/F_{MSY}$	Average fishing mortality-at-age for a recent period relative to F_{MSY}
B_0	Equilibrium unexploited total biomass
B_{MSY}	Equilibrium total biomass that results from fishing at F_{MSY}
B_{MSY}/B_0	Equilibrium total biomass that results from fishing at F_{MSY} relative to B_0
$B_{current}$	Average annual total biomass over a recent period
B_{latest}	Total annual biomass in the most recent year
$B_{F_{current}}$	Equilibrium total biomass that results from fishing at $F_{current}$
$B_{current_{F=0}}$	Average annual total biomass over a recent period in the absence of fishing
$B_{latest_{F=0}}$	Total biomass predicted to exist in the absence of fishing
SB_0	Equilibrium unexploited total biomass ⁶ .
$B_{current}/B_0$	Average annual total biomass over a recent period relative to B_0
B_{latest}/B_0	Total annual biomass in the most recent year relative to B_0
$B_{F_{current}}/B_0$	Equilibrium total biomass that results from fishing at $F_{current}$ relative to B_0
$B_{current}/B_{MSY}$	Average annual total biomass over a recent period relative to B_{MSY}
B_{latest}/B_{MSY}	Total annual biomass in the most recent year relative to B_{MSY}
$B_{F_{current}}/B_{MSY}$	Equilibrium total biomass that results from fishing at $F_{current}$ relative to B_{MSY}
$B_{current}/B_{current_{F=0}}$	Average annual total biomass over a recent period / the biomass in the absence of fishing
$B_{latest}/B_{latest_{F=0}}$	Total annual biomass in the most recent year / the biomass in the absence of fishing
$Crit_{age}$	The age at which harvest would maximize the yield per recruit
$Crit_{length}$	The length at which harvest would maximize the yield per recruit
$Mean_{age}$	The mean age of the catch over a recent period
$Mean_{length}$	The mean length of the catch over a recent period
Y_{lost}	The proportion of the maximum yield per recruit lost by the mean age at harvest

³ Some recent period used for the purpose of averaging fishing mortality or other quantities. Typically excludes the most recent year due to uncertainty, but covers the preceding four years, e.g. 2006-2009.

⁴ This age-specific pattern is dependent on both the amount of fishing and the mix of fishing gears, e.g. relative catches of small and large fish

⁵ MSY and other MSY -related quantities are linked to a particular fishing pattern and the MSY will change, for example, based on changes in the relative catches of small and large fish

⁶ Similar quantities as above for total biomass can also be calculated for spawning biomass and are not repeated here

Table 8. Estimates of management quantities for the reference case and key model runs. The highlighted rows are comparable quantities at the same point in time and ratios of comparable equilibrium quantities (gray shading).

	Run13 (Ref.case)	Run14 (sel_JP_A U_3log)	Run15 (CP_JP1)	Run20 (CP_JP2_A U_2_3)	Run25 (h=0.65)	Run26 (h=0.95)	Run27 (M0.2)	Run28 (M0.6)
$C_{current}$	1758	1753	1856	1785	1759	1759	1744	1767
C_{latest}	1522	1523	1607	1512	1522	1522	1514	1526
$Y_{F_{current}}$	2060	2013	1877	2199	1890	2135	1475	2282
$Y_{F_{MSY}}$ or MSY	2081	2017	3161	2256	1914	2276	1877	2829
$Y_{F_{current}}/MSY$	0.99	1.00	0.59	0.98	0.99	0.94	0.79	0.81
$C_{current}/MSY$	0.85	0.87	0.59	0.79	0.92	0.77	0.93	0.63
C_{latest}/MSY	0.73	0.76	0.51	0.67	0.80	0.67	0.81	0.54
F_{MSY}	0.28	0.28	0.28	0.28	0.22	0.36	0.20	0.32
F_{mult}	1.24	1.10	4.06	1.39	0.83	1.98	0.45	3.39
$F_{current}/F_{MSY}$	0.81	0.91	0.25	0.72	1.21	0.51	2.21	0.30
B_0	19,240	18,470	31,060	21,090	21,340	18,080	28,680	20,180
B_{MSY}	7331	7123	11220	7987	8662	6385	9206	8753
B_{MSY}/B_0	0.38	0.39	0.36	0.38	0.406	0.35	0.32	0.43
$B_{current}$	6055	5620	19,105	6677	6070	6075	4123	9050
B_{latest}	6642	6170	19,315	7328	6629	6681	4313	10,216
$B_{F_{current}}$	8224	7491	22,350	9582	7568	8542	4152	13,180
$B_{current_{F=0}}$	13,135	12,691	26,322	13,807	13,151	13,155	20,793	13,286
$B_{latest_{F=0}}$	13,252	12,771	26,063	13,964	13,239	13,292	20,074	14,186
SB_0	15,130	14,530	24,430	16,590	16,790	14,220	25,920	13,470
SB_{MSY}	4091	3987	6218	4461	5314	3137	6983	3600
SB_{MSY}/SB_0	0.27	0.27	0.26	0.27	0.32	0.22	0.27	0.27
$SB_{current}$	3567	3236	13,991	4116	3583	3579	2598	4834
SB_{latest}	3698	3345	13,642	4113	3703	3718	2616	5071
$SB_{F_{current}}$	4834	4290	16,120	5802	4453	5025	2588	7045
$SB_{current_{F=0}}$	10,473	10,134	21,051	11077	10490	10,486	19,069	8916
$SB_{latest_{F=0}}$	10,140	9,777	20,237	10577	10145	10,162	18,179	8895
$B_{current}/B_0$	0.32	0.30	0.62	0.32	0.28	0.34	0.14	0.45
B_{latest}/B_0	0.35	0.33	0.62	0.35	0.31	0.37	0.15	0.51
$B_{F_{current}}/B_0$	0.43	0.41	0.72	0.45	0.36	0.47	0.15	0.65
$B_{current}/B_{MSY}$	0.83	0.79	1.70	0.84	0.70	0.95	0.45	1.03
B_{latest}/B_{MSY}	0.91	0.87	1.72	0.92	0.77	1.05	0.47	1.17
$B_{F_{current}}/B_{MSY}$	1.12	1.05	1.99	1.20	0.87	1.34	0.45	1.51
$B_{current}/B_{current_{F=0}}$	0.46	0.44	0.73	0.48	0.46	0.46	0.20	0.68
$B_{latest}/B_{latest_{F=0}}$	0.50	0.48	0.74	0.53	0.50	0.50	0.22	0.72
$SB_{current}/SB_0$	0.24	0.22	0.57	0.25	0.21	0.25	0.10	0.36
SB_{latest}/SB_0	0.24	0.23	0.56	0.25	0.22	0.26	0.10	0.38
$SB_{F_{current}}/SB_0$	0.32	0.30	0.66	0.35	0.27	0.35	0.10	0.52
$SB_{current}/SB_{MSY}$	0.87	0.81	2.25	0.92	0.67	1.14	0.37	1.34
SB_{latest}/SB_{MSY}	0.90	0.84	2.19	0.92	0.70	1.19	0.38	1.41
$SB_{F_{current}}/SB_{MSY}$	1.18	1.08	2.59	1.30	0.84	1.60	0.37	1.96
$SB_{curr}/SB_{curr_{F=0}}$	0.34	0.32	0.67	0.37	0.34	0.34	0.14	0.54
$SB_{latest}/SB_{latest_{F=0}}$	0.37	0.34	0.67	0.39	0.37	0.37	0.14	0.57
Steepness (h)	0.80	0.80	0.80	0.80	0.65	0.95	0.80	0.80

Table 8 cont.

	Run13 (Ref.case)	Run29 (Growth_ est)	Run30 (Sz_data_ wt)	Run31 (msy_recent)	Grid median	Grid 5%ile	Grid 95%ile
$C_{current}$	1758	1707	1764	1762	1745	1685	1854
C_{latest}	1522	1476	1521	1526	1522	1453	1621
$Y_{F_{current}}$	2060	2032	2115	1815	1890	1207	2408
$Y_{F_{MSY}}$ or MSY	2081	2182	2179	1839	2182	1744	7350
$Y_{F_{current}}/MSY$	0.99	0.93	0.97	0.99	0.86	0.24	1.00
$C_{current}/MSY$	0.85	0.78	0.81	0.96	0.81	0.24	0.99
C_{latest}/MSY	0.73	0.68	0.70	0.83	0.70	0.21	0.87
F_{MSY}	0.28	0.30	0.29	0.28	0.27	0.15	0.40
F_{mult}	1.24	1.79	1.42	1.27	1.71	0.40	12.94
$F_{current}/F_{MSY}$	0.81	0.56	0.71	0.79	0.58	0.08	2.53
B_0	19,240	19,140	20,340	17,080	24,050	16,554	63,104
B_{MSY}	7331	7285	7607	6502	8662	6297	24,474
B_{MSY}/B_0	0.38	0.38	0.37	0.38	0.37	0.28	0.45
$B_{current}$	6055	7176	6644	6205	7120	4156	35,681
B_{latest}	6642	7741	7388	6784	7680	4369	39,307
$B_{F_{current}}$	8224	9786	9248	7407	9699	3810	55,964
$B_{currentF=0}$	13,135	13,450	13,742	13,291	17,791	12,447	39,733
$B_{latestF=0}$	13,252	13,591	14,009	13,400	18,084	12,785	42,906
SB_0	15,130	15,360	16,000	13,440	18,490	11,100	41,056
SB_{MSY}	4091	4329	4214	3633	4960	2763	11,760
SB_{MSY}/SB_0	0.27	0.28	0.26	0.27	0.27	0.20	0.32
$SB_{current}$	3567	4791	4008	3683	4270	2625	22,863
SB_{latest}	3698	4921	4205	3813	4438	2628	22,580
$SB_{F_{current}}$	4834	6499	5593	4387	5604	2390	34,564
$SB_{currentF=0}$	10,473	10,928	10,935	10,595	12,997	8150	31,963
$SB_{latestF=0}$	10,140	10,632	10,658	10,262	12,513	8332	31,004
$B_{current}/B_0$	0.32	0.38	0.33	0.36	0.36	0.14	0.75
B_{latest}/B_0	0.35	0.40	0.36	0.40	0.39	0.14	0.76
$B_{F_{current}}/B_0$	0.43	0.51	0.46	0.43	0.49	0.12	0.89
$B_{current}/B_{MSY}$	0.83	0.99	0.87	0.95	0.96	0.37	1.96
B_{latest}/B_{MSY}	0.91	1.06	0.97	1.04	1.06	0.39	2.00
$B_{F_{current}}/B_{MSY}$	1.12	1.34	1.22	1.14	1.29	0.32	2.31
$B_{current}/B_{currentF=0}$	0.46	0.53	0.48	0.47	0.52	0.20	0.89
$B_{latest}/B_{latestF=0}$	0.50	0.57	0.53	0.51	0.55	0.22	0.90
$SB_{current}/SB_0$	0.24	0.31	0.25	0.27	0.29	0.10	0.73
SB_{latest}/SB_0	0.24	0.32	0.26	0.28	0.30	0.10	0.70
$SB_{F_{current}}/SB_0$	0.32	0.42	0.35	0.33	0.39	0.09	0.85
$SB_{current}/SB_{MSY}$	0.87	1.11	0.95	1.01	1.09	0.32	2.89
SB_{latest}/SB_{MSY}	0.90	1.14	1.00	1.05	1.14	0.33	2.78
$SB_{F_{current}}/SB_{MSY}$	1.18	1.50	1.33	1.21	1.44	0.28	3.38
$SB_{curr}/SB_{currF=0}$	0.34	0.44	0.37	0.35	0.43	0.14	0.85
$SB_{latest}/SB_{latestF=0}$	0.37	0.46	0.40	0.37	0.46	0.14	0.86
Steepness (h)	0.80	0.80	0.80	0.80	-	-	-

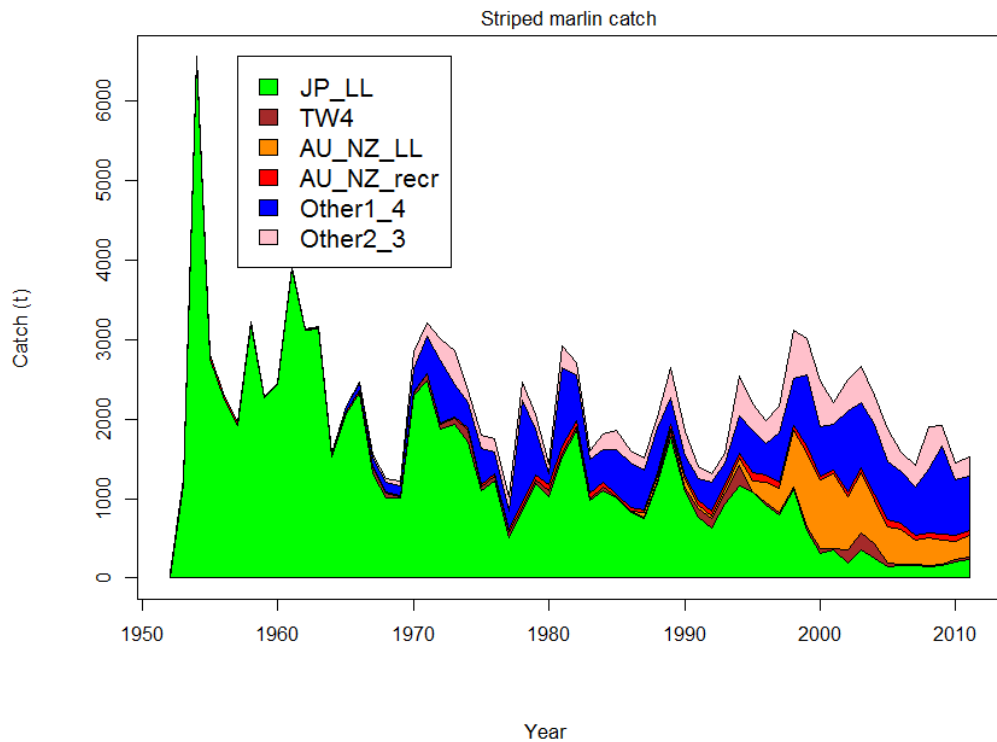
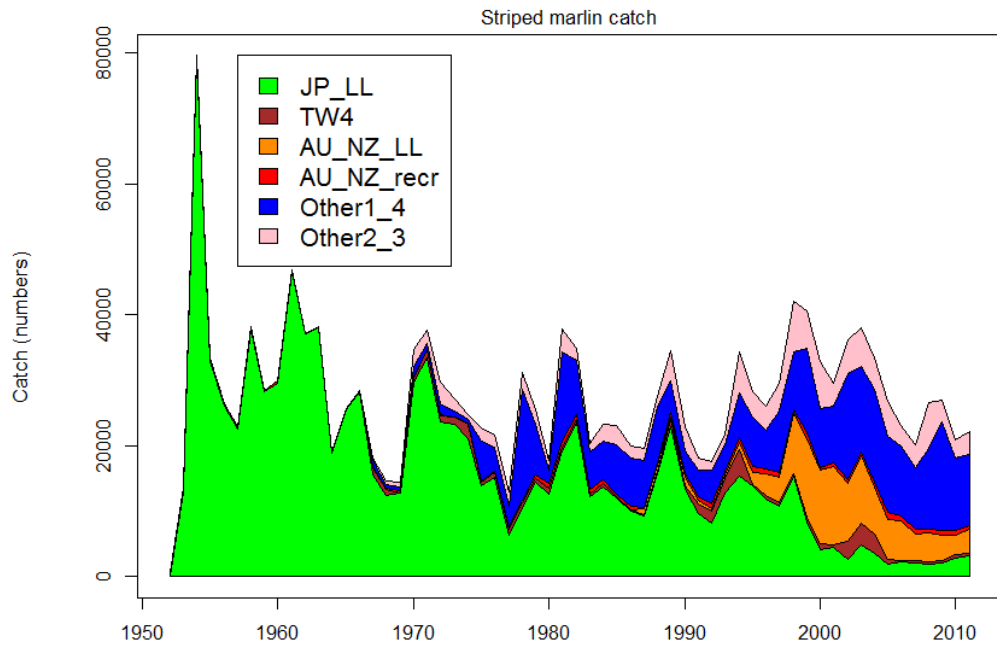


Figure 1. Total striped marlin catches (numbers top, weight bottom) grouped by major longline-method fisheries in the model region, 1952–2011: JP_LL - Japan; TW4 – Taiwan area 4; AU_NZ_LL – Australia and New Zealand; AU_NZ_rec - Australia and New Zealand recreational; Other1_4 and Other2_3 – other LL in areas 1 &4 and 2 & 3, respectively.

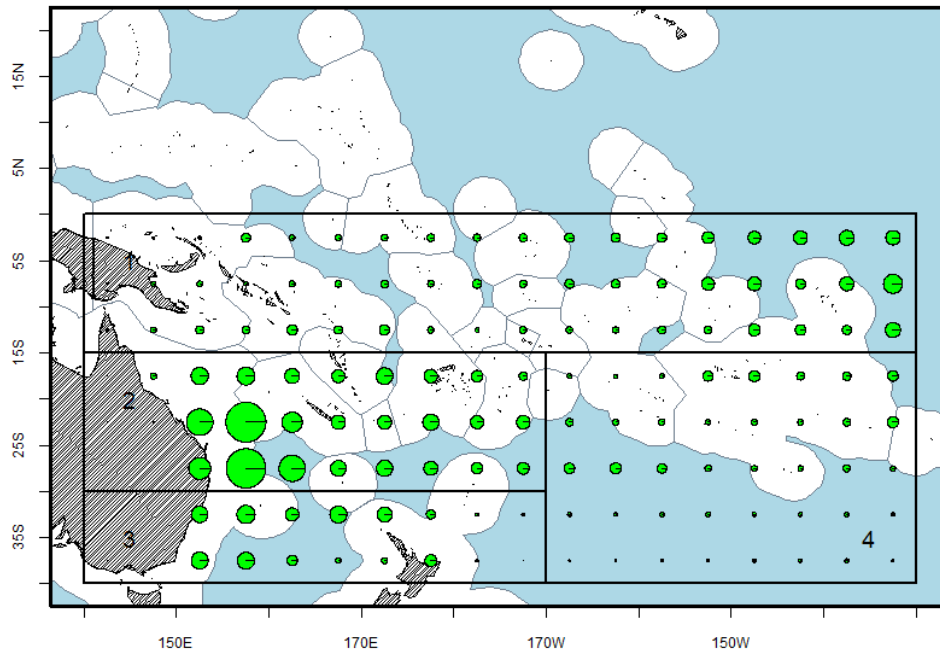


Figure 2. Catches of striped marlin (numbers) in the southwest Pacific, 1952–2011. Source: raised catch estimates available from the SPC. The black lines represent the boundaries of the assessment region (outer lines) for striped marlin in the southwest Pacific Ocean and the four sub-areas within the assessment region.

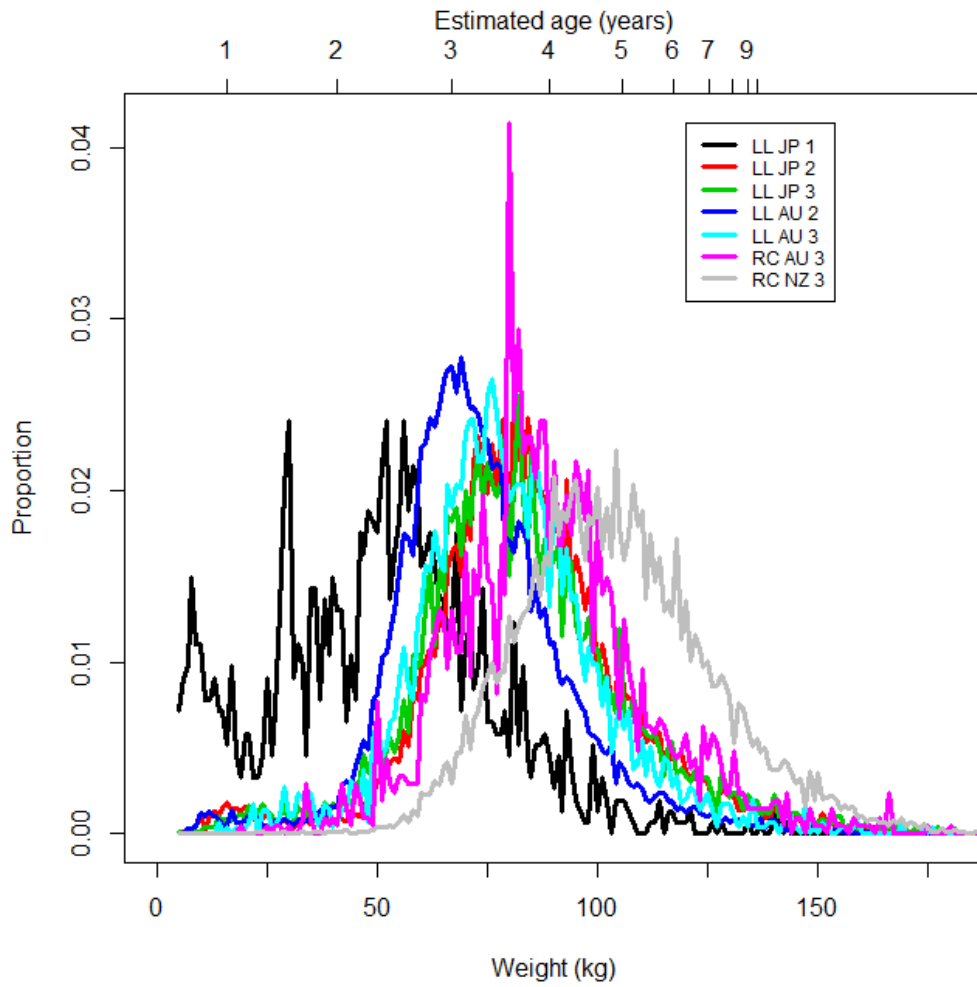


Figure 3. A comparison of the weight (whole weight, kilogrammes) frequency distributions of the sampled catches from the main fisheries, all years combined.

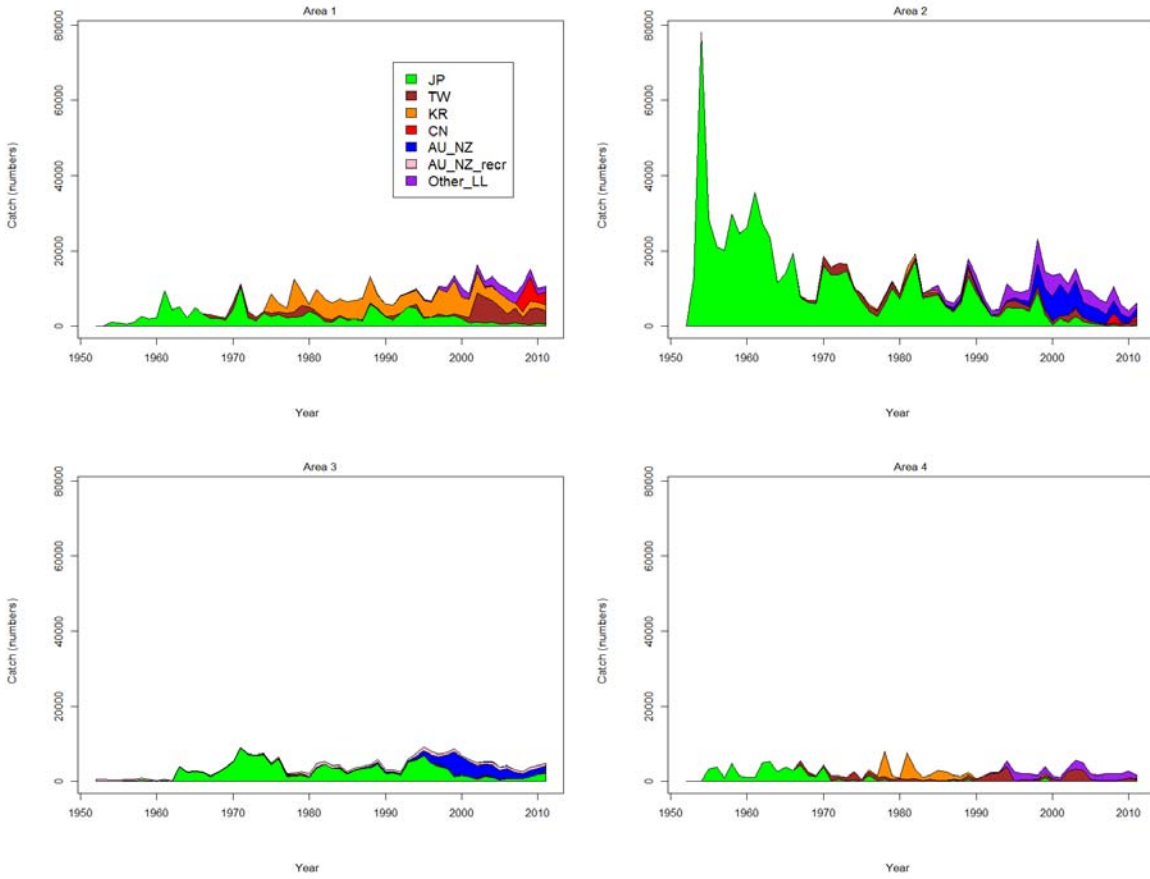


Figure 4. Total estimated catches of striped marlin (numbers) by major flag, method-fishery and sub-area from the assessment model for the southwest Pacific, 1952–2011.

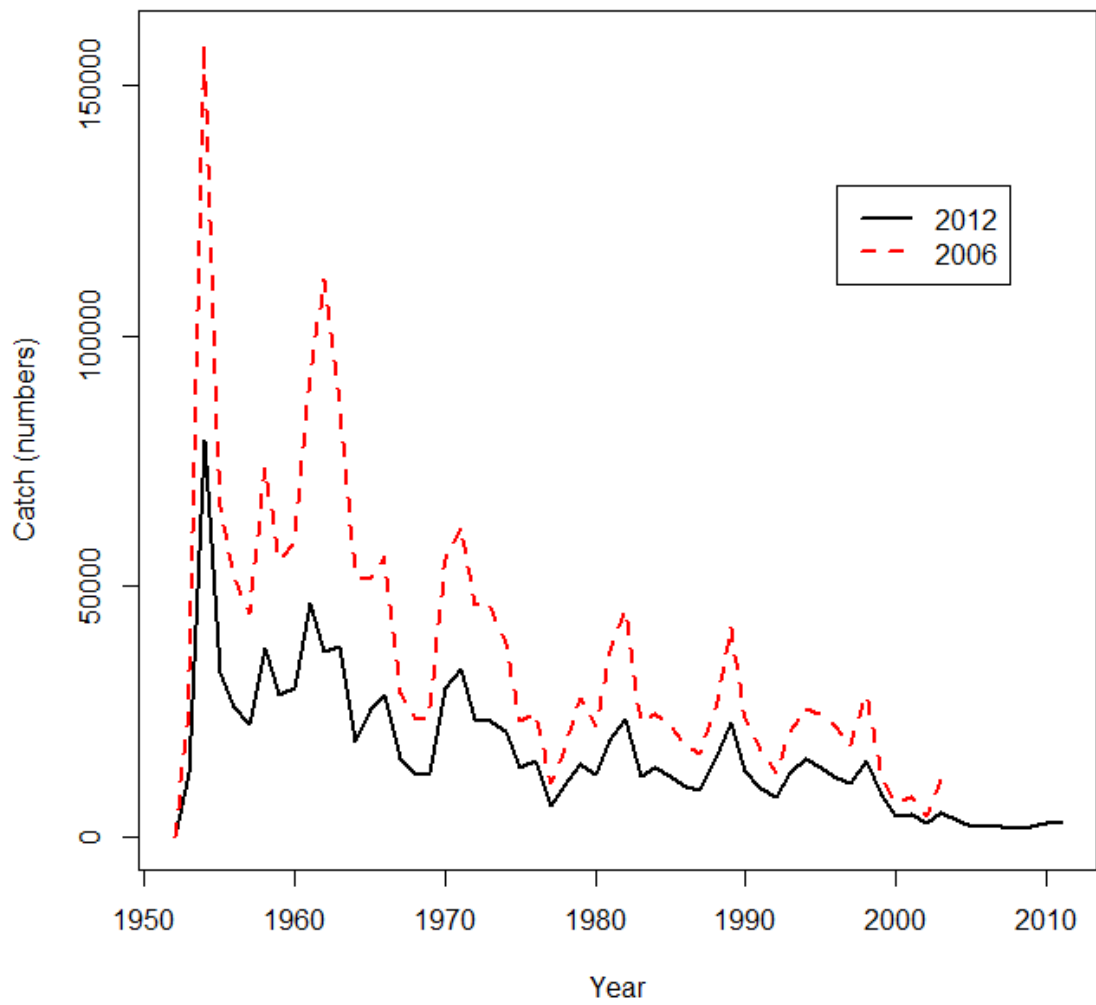


Figure 5. Comparison between the total catches of striped marlin (numbers) by the Japanese longline fishery, 1952–2011, applied in the 2006 and 2012 stock assessments.

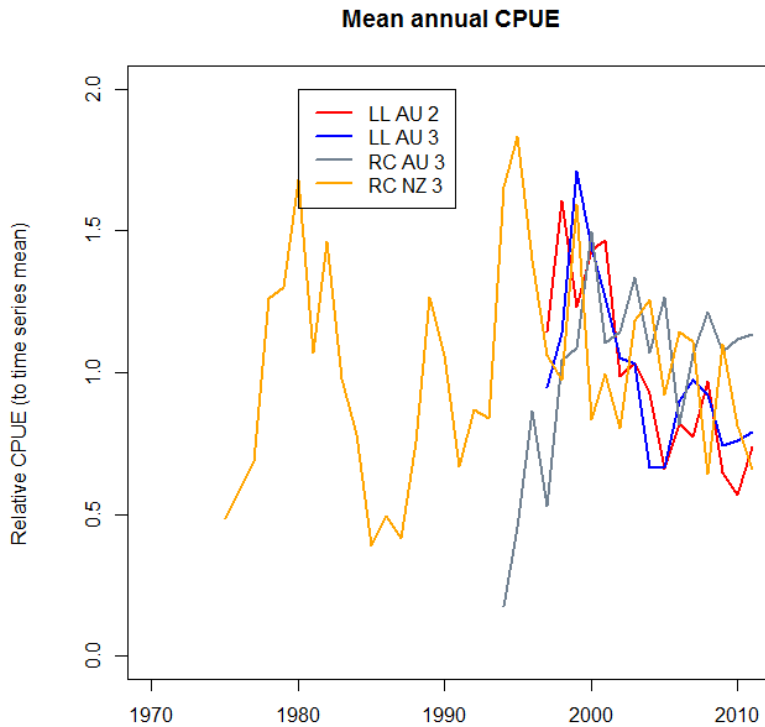
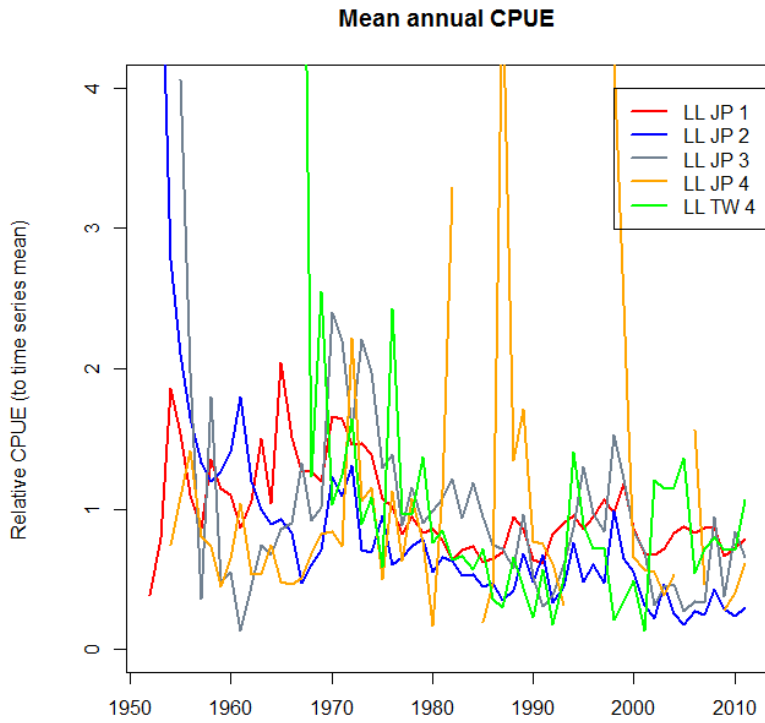


Figure 6. A comparison of the main CPUE indices for nine of the fourteen fisheries included in the model. The CPUE series are normalised to the mean of each series and smoothed using a lowess function.

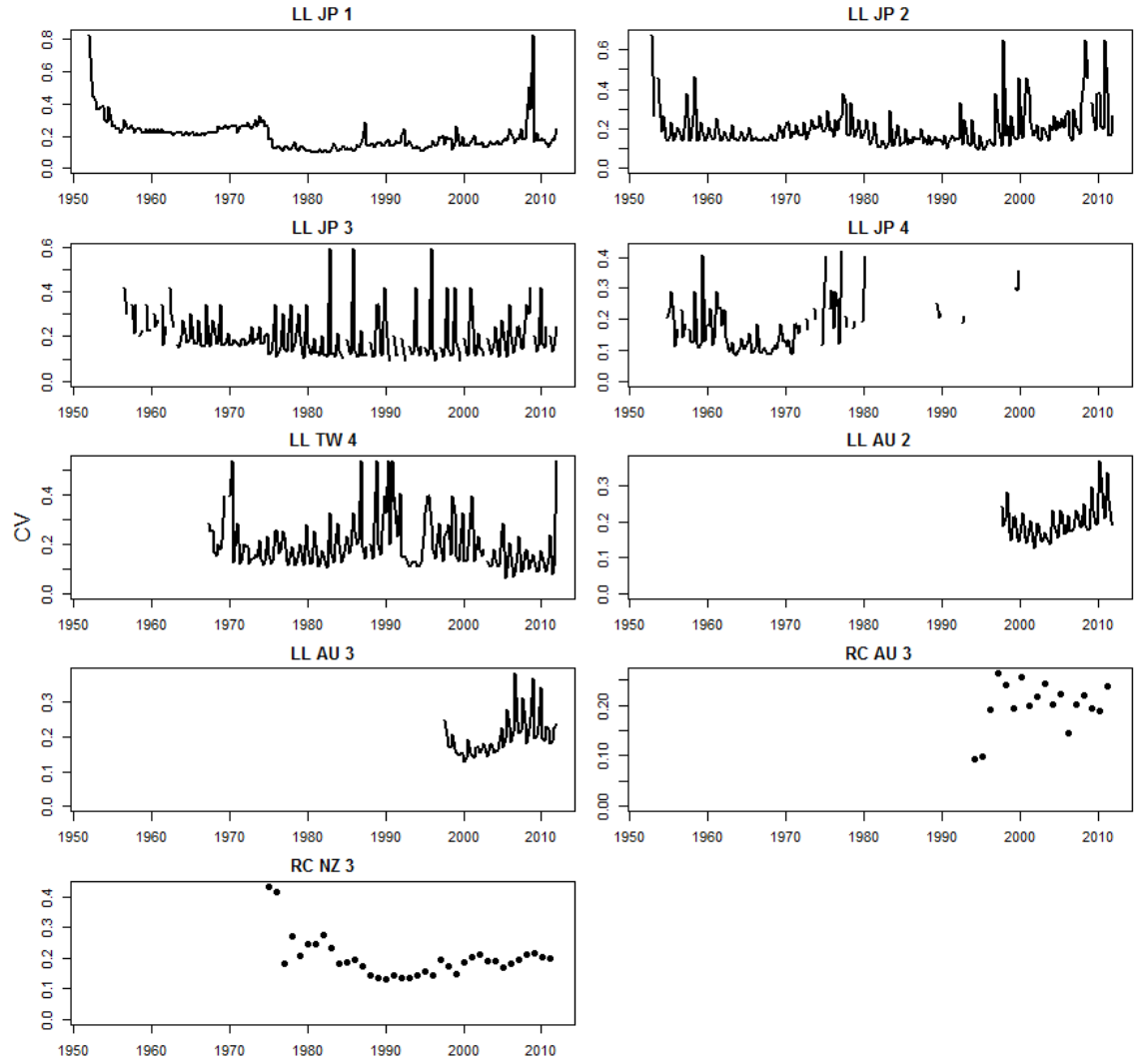


Figure 7: Temporal variation in precision (CV) of standardised CPUE indices for the nine fisheries defined in the model.

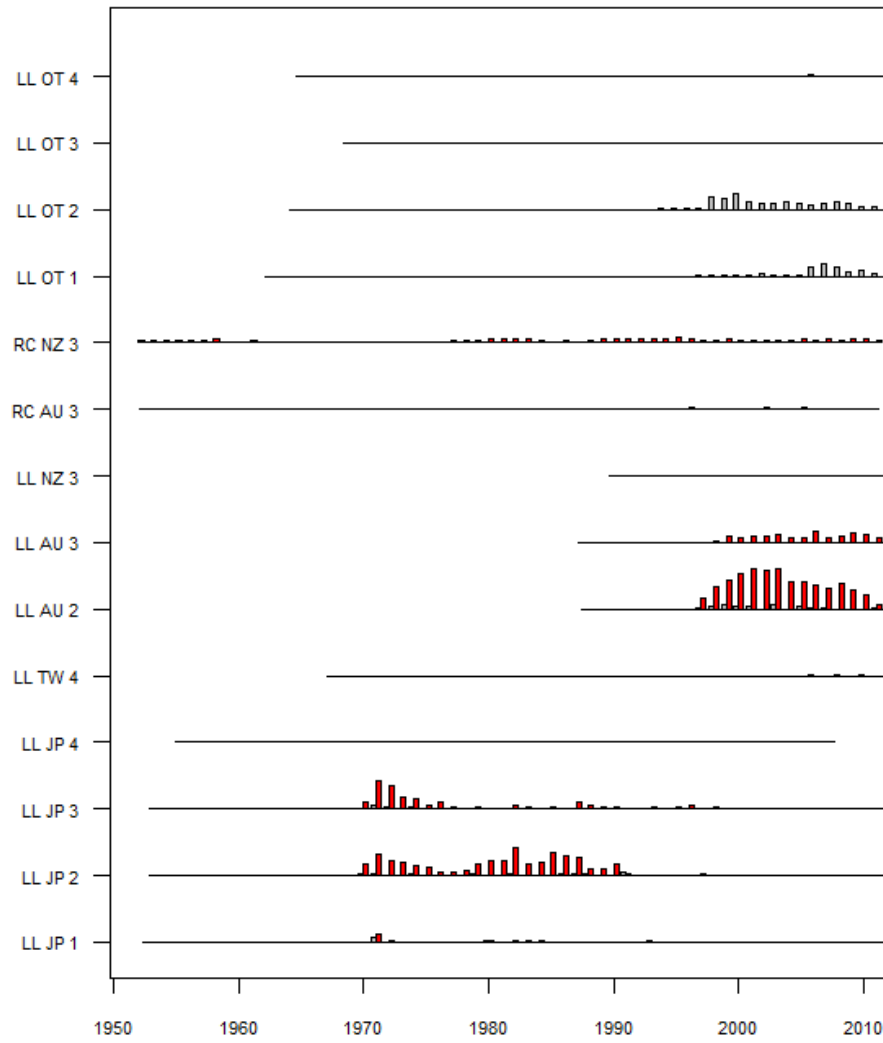


Figure 8. Number of fish size measurements by year for each fishery. The grey bars represent length measurements and the red bars represent weight measurements. The maximum bar length is 1615 fish. The extent of the horizontal lines indicates the period over which each fishery occurred.

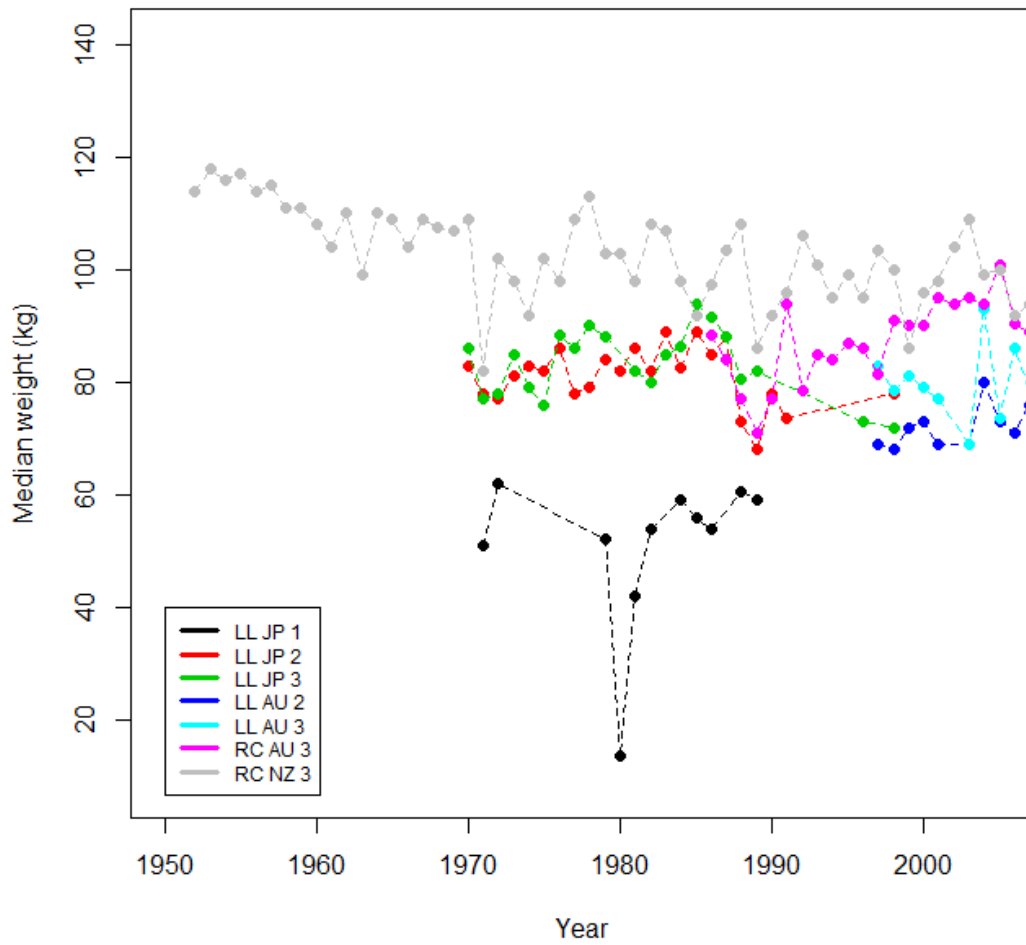


Figure 9. Trends in median fish weight (whole weight, kilogrammes) by year for the main fisheries providing size frequency data. Only years with at least 30 sampled fish are presented.

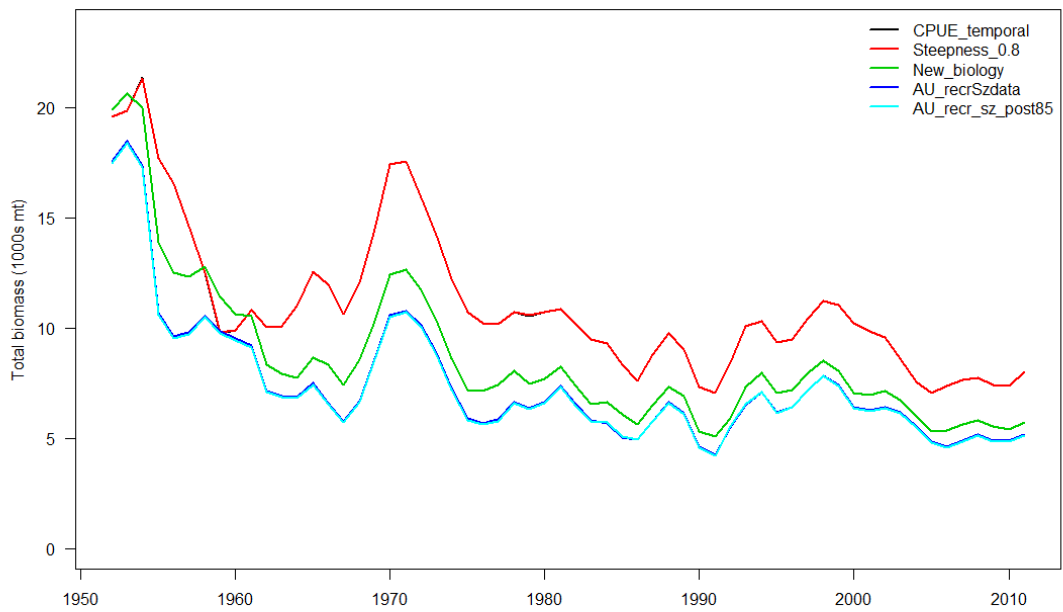
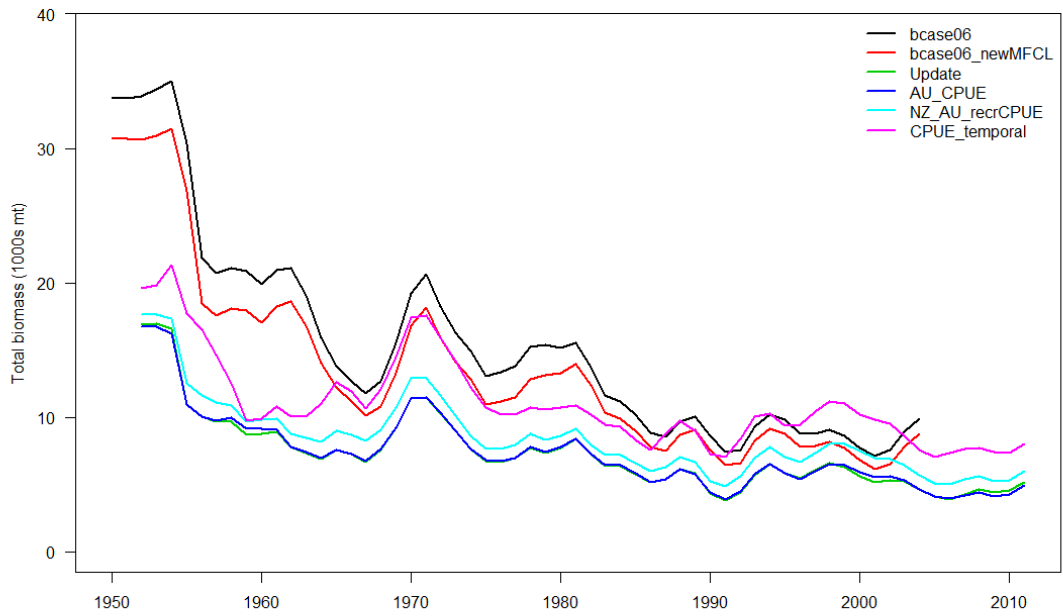


Figure 10: Total biomass of models as a stepwise progression from the base case of the 2006 striped marlin stock assessment towards the Ref.case model of the 2012 assessment. Runs are defined in Table 5.

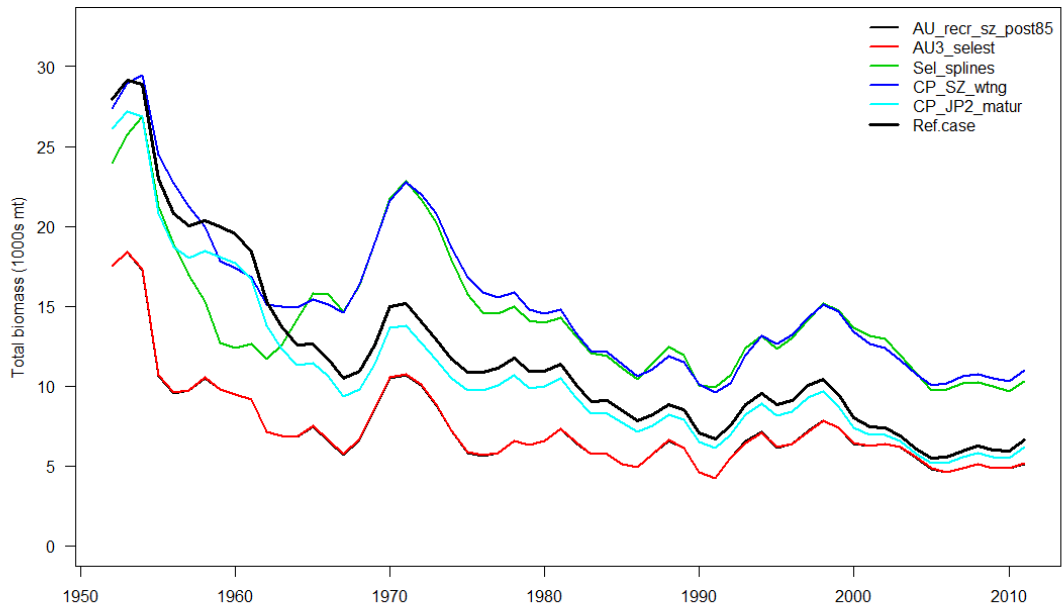


Figure 10 cont.

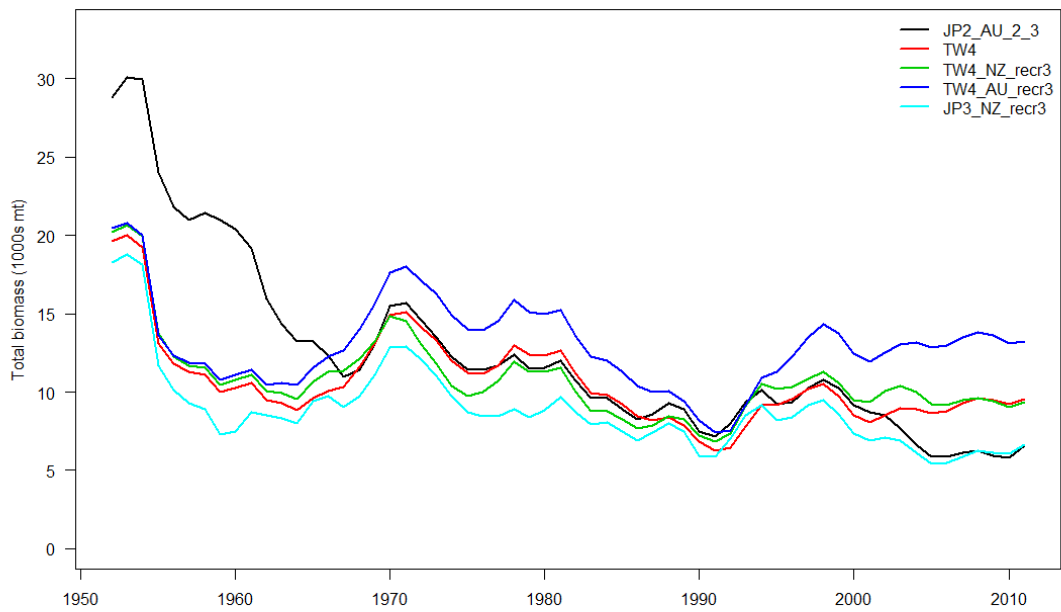
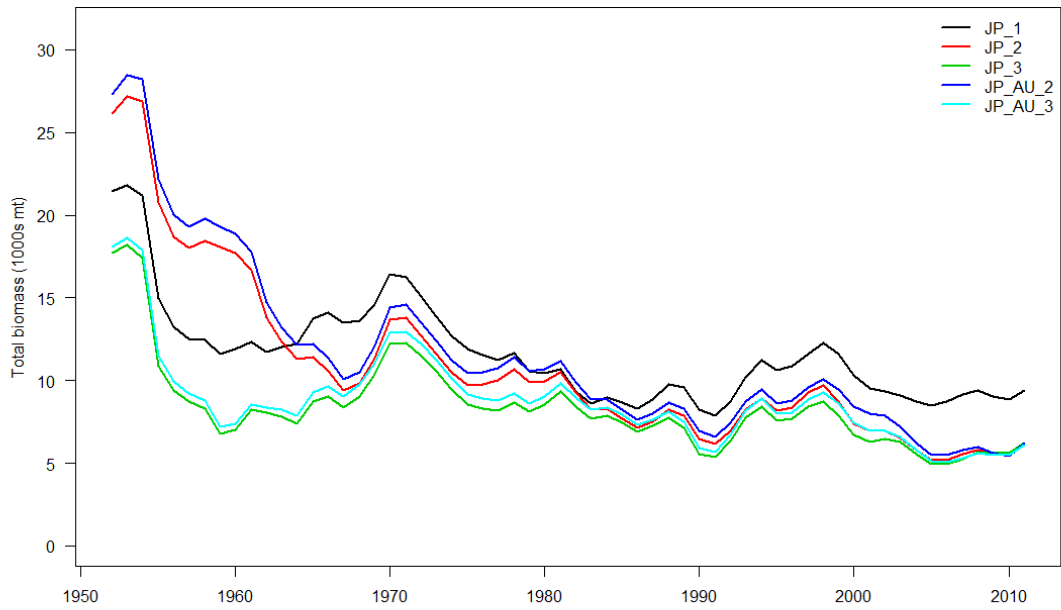


Figure 11a. Sensitivity of the Sel_JP_AU3_log model to the standardised CPUE indices included in the model fit.

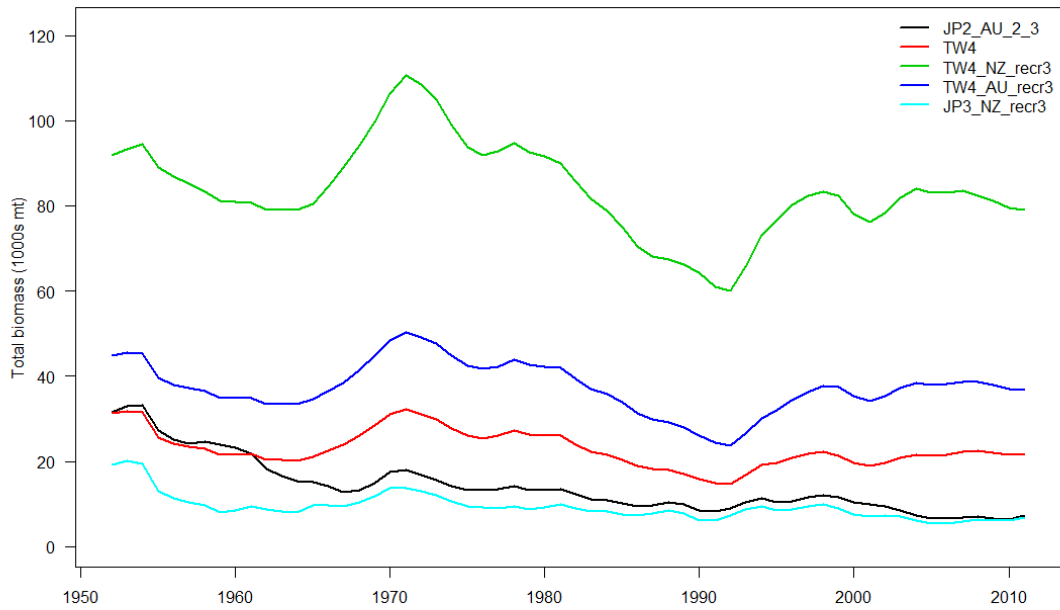
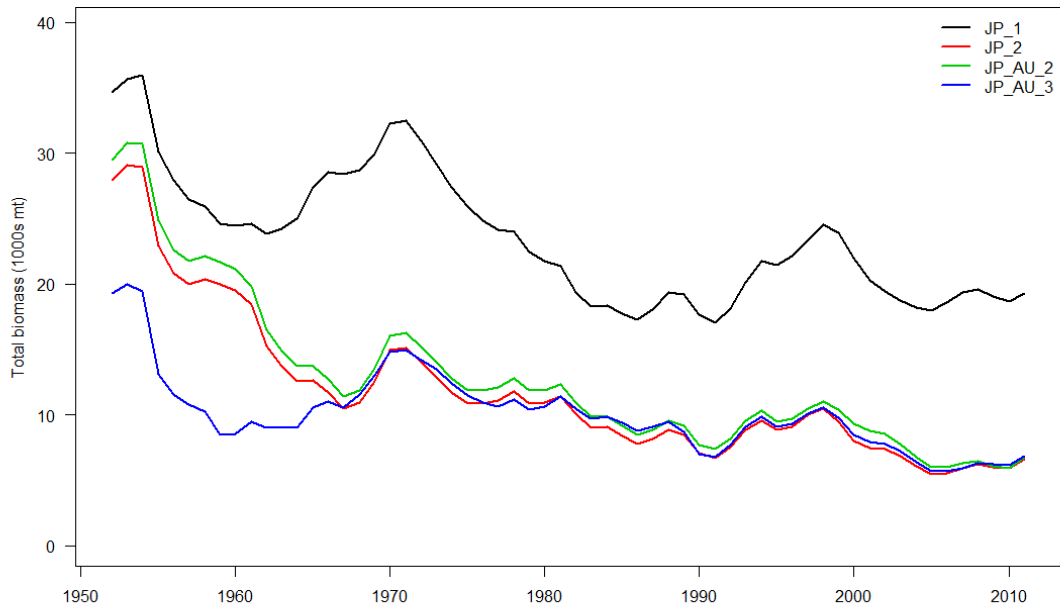


Figure 11b. Sensitivity of the Ref.case model to the standardised CPUE indices included in the model fit.

Likelihood profiles for MLS model options

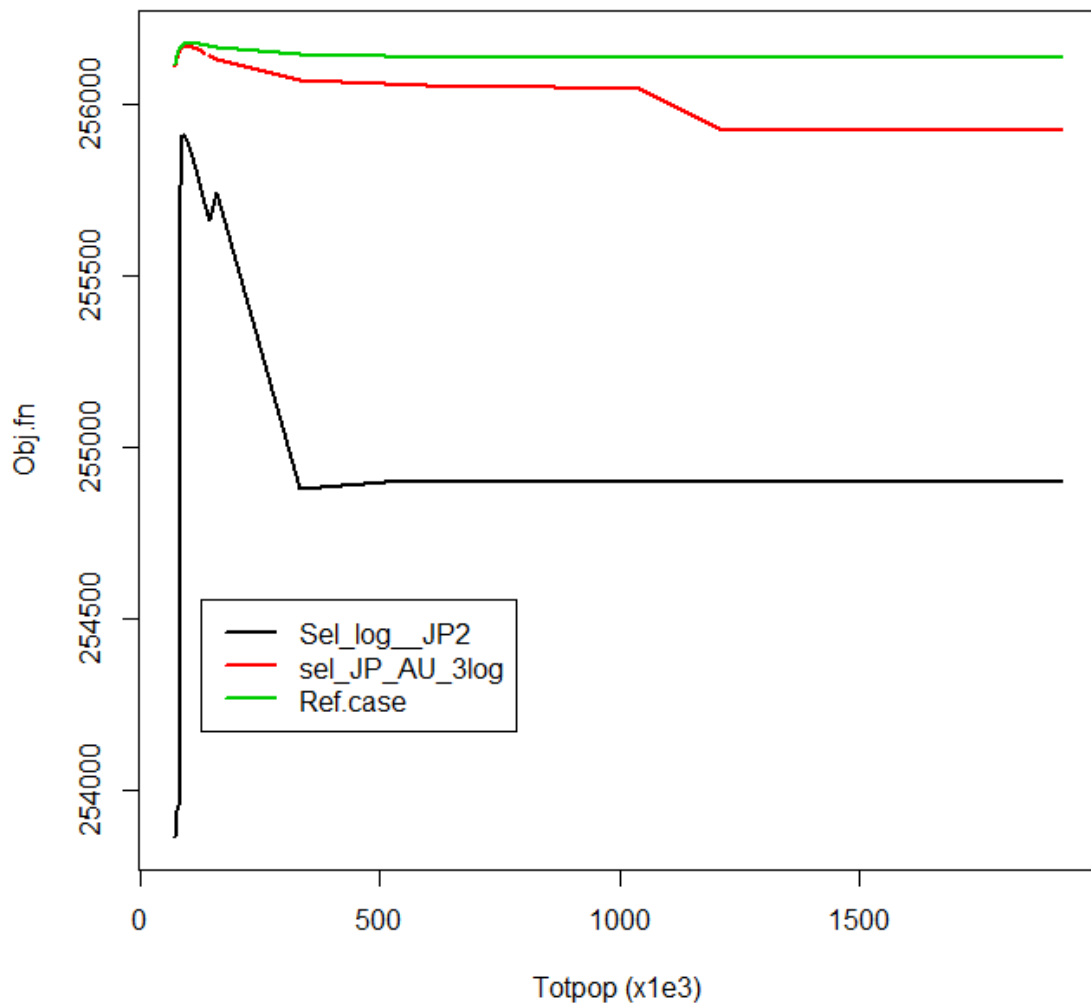


Figure 12: Likelihood profiles with respect to the total population scaling parameter (Totpop) for three model options for selectivity assumptions: Sel_log_JP2 – logistic functions all fisheries except spline functions for JP1, OT1, JP4, OT4, TW5; sel_JP_AU_3log – spline functions for all fisheries except logistic functions for JP3, OT3, AU3 and recreational fisheries; and, Ref.case - spline functions for all fisheries except logistic functions for recreational fisheries; and all models were fitted to the JP2 standardised CPUE time series.

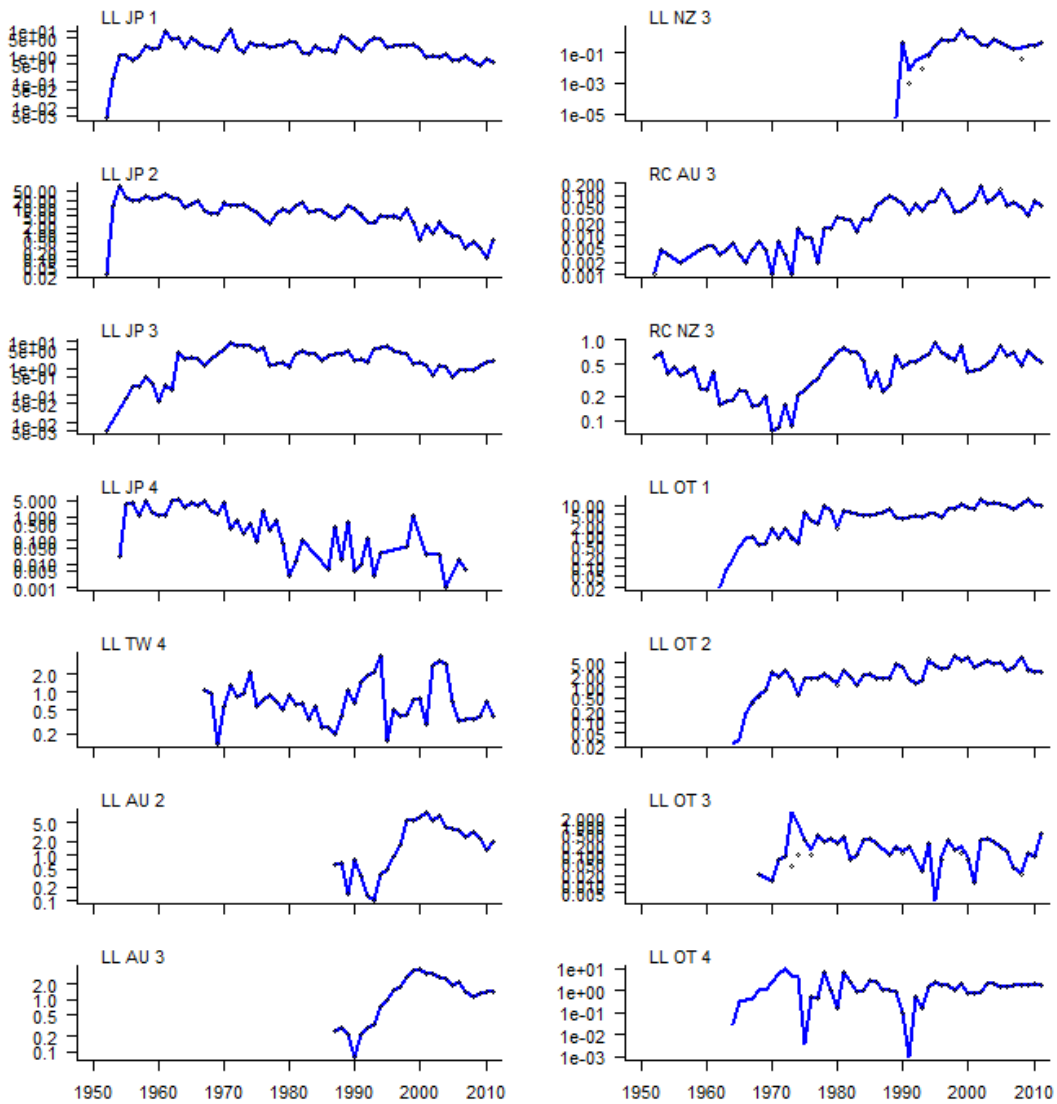


Figure 13. Observed (points) and Ref.case model predicted (blue line) annual catches, by fishery. Catches are expressed as number of fish. The y-axes are plotted on a logarithmic scale.

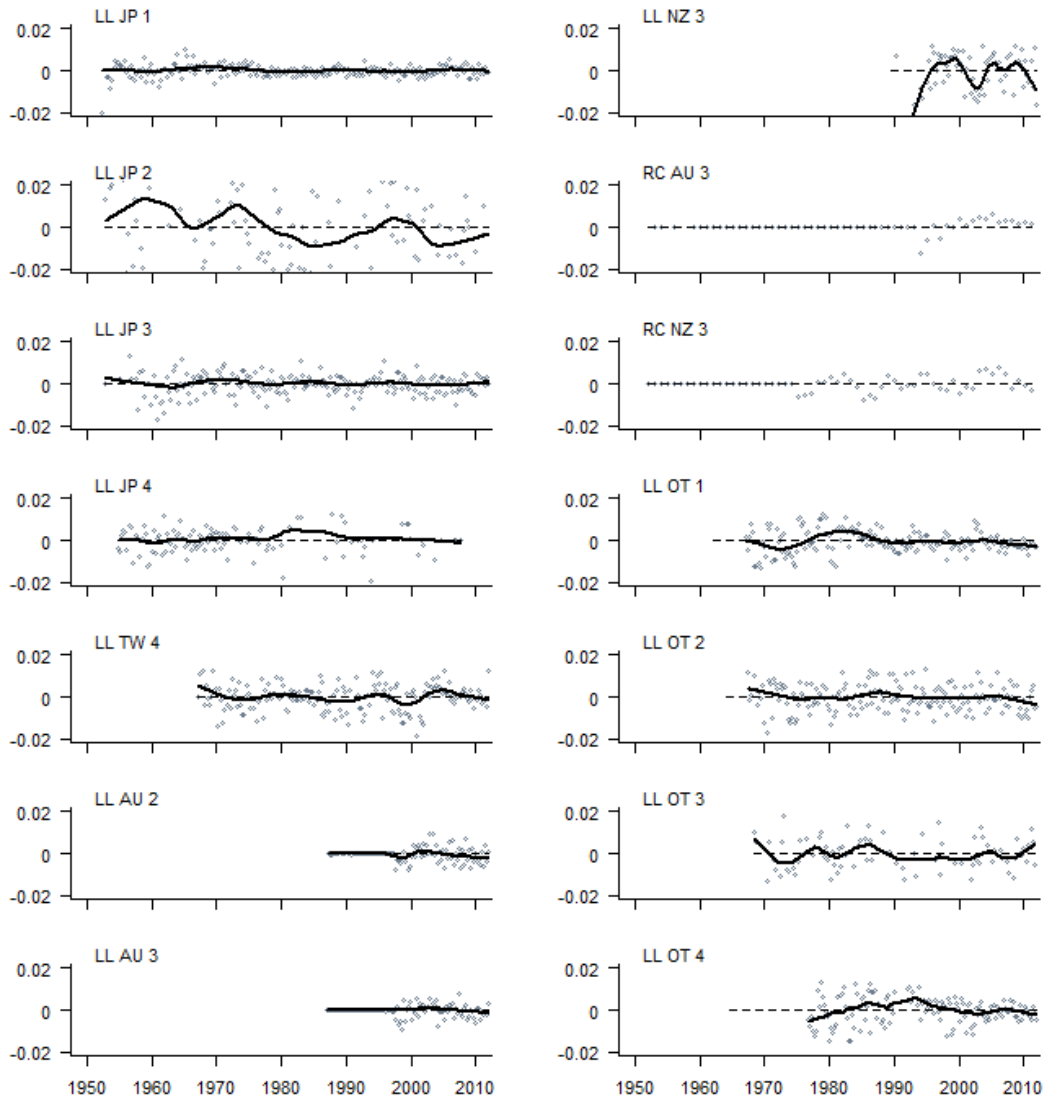


Figure 14. Residuals (ln) of total catch for each fishery. Solid lines represent lowess fits to the data.

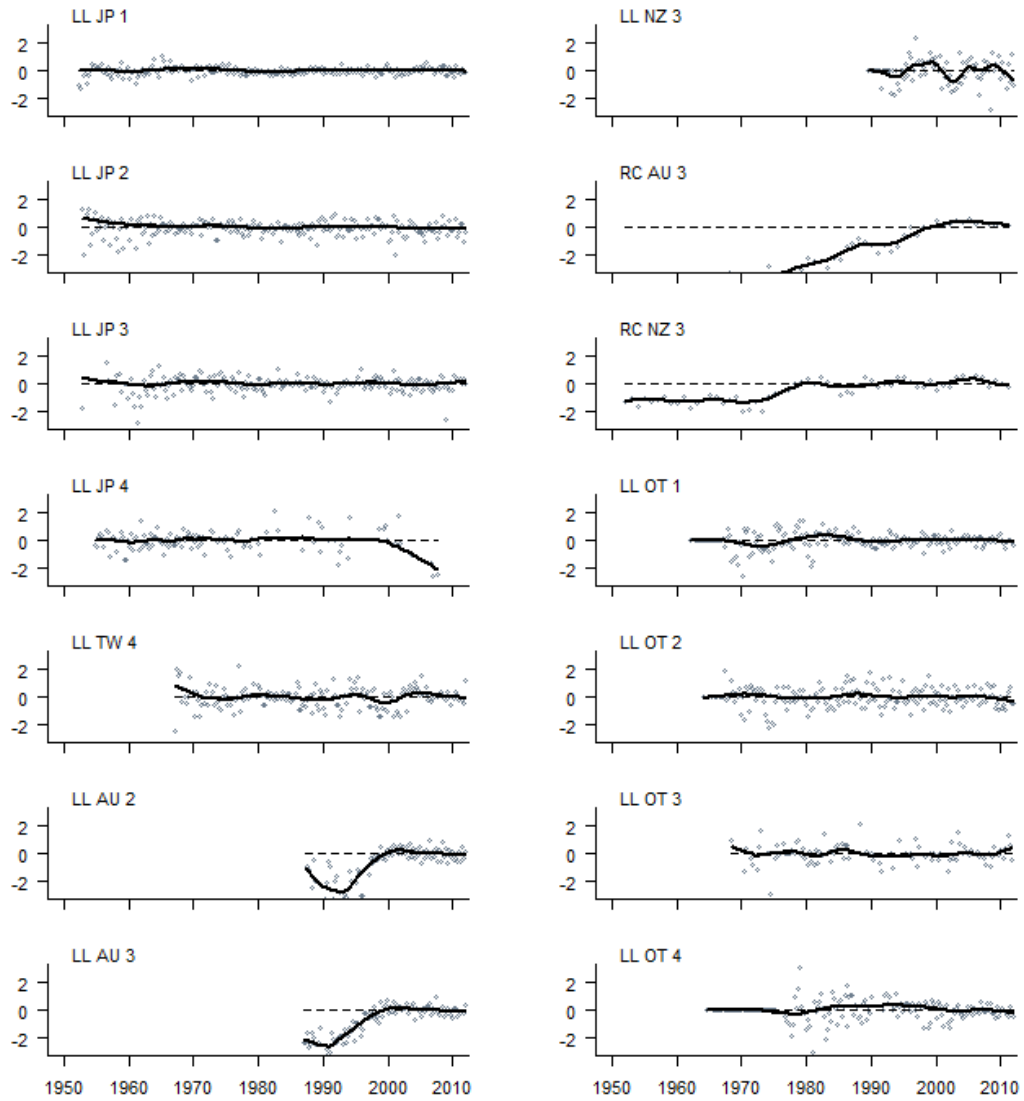


Figure 15. Effort deviations by time period for each fishery. Solid lines represent lowess fits to the data. Model estimates are from the model using natural mortality of 0.4 per year, $k = 0.6$, and the uninformative prior on steepness of the SSR.

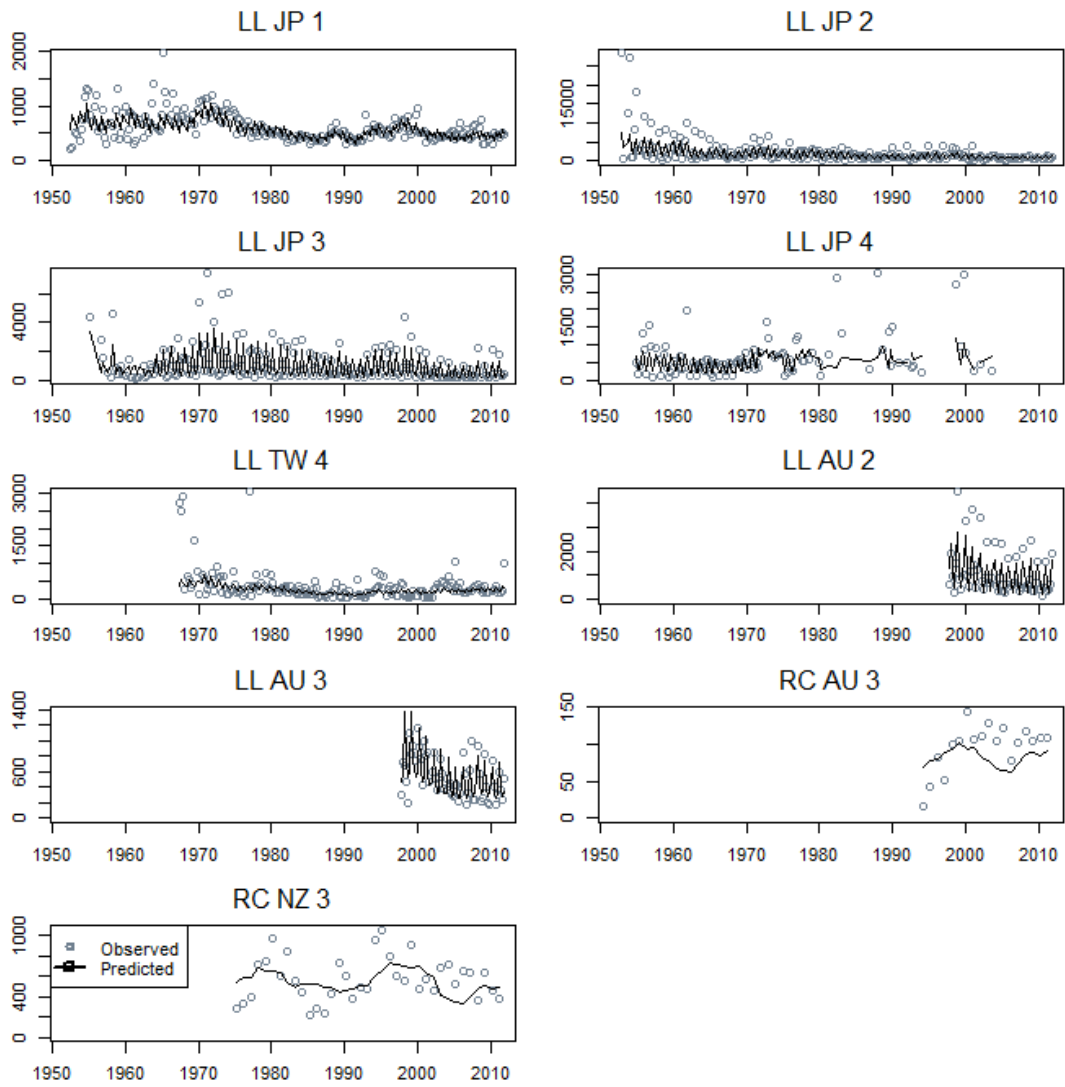


Figure 16. A comparison between observed CPUE (points) and fishery specific exploitable biomass (line) for the main fisheries included in the model. Model estimates are from the model using natural mortality of 0.4 per year, $k = 0.6$, and the uninformative prior on steepness of the SSR.

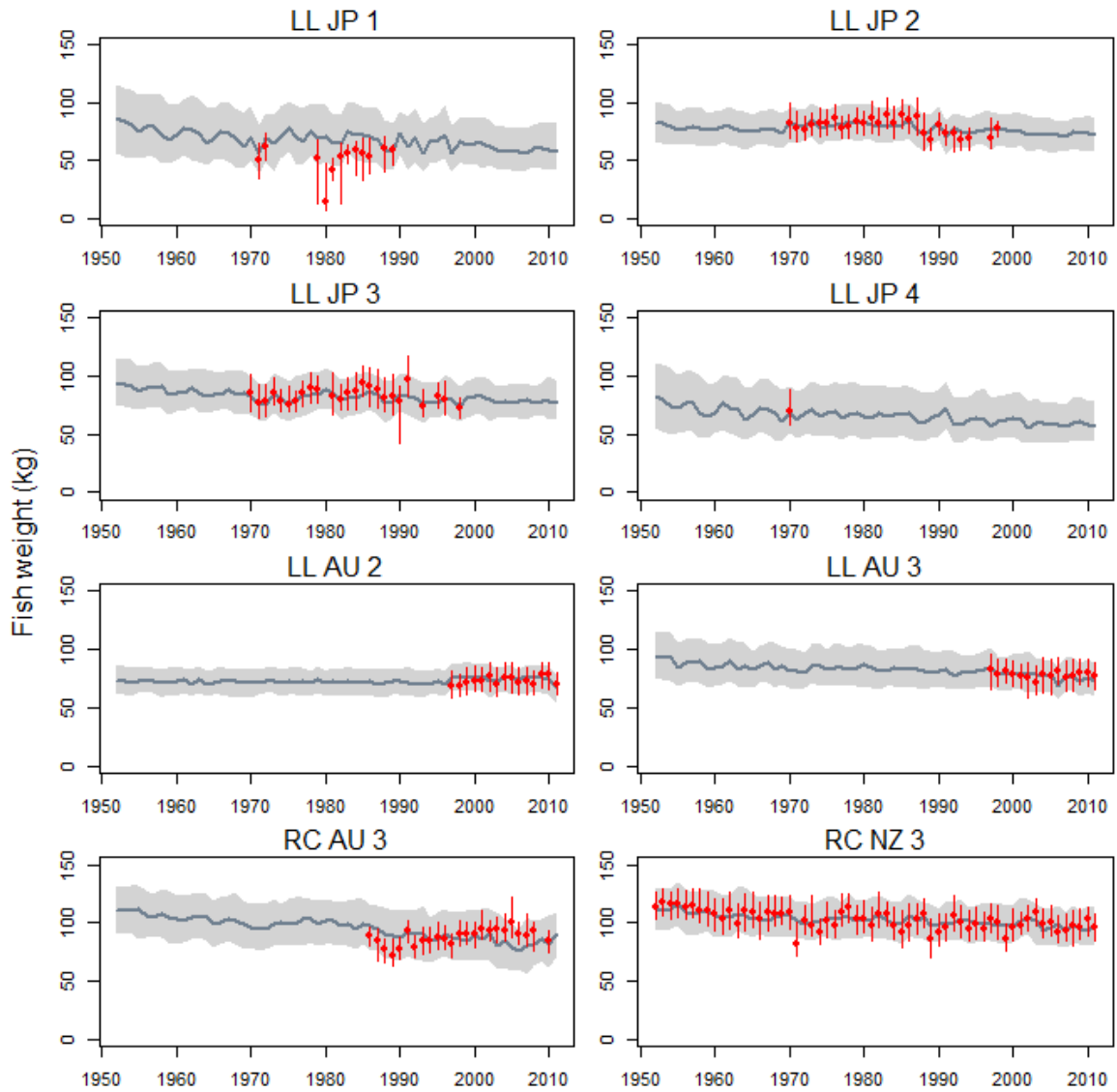


Figure 17. A comparison of the observed (points) and predicted (grey line) annual median weight (whole weight, kilogrammes) of striped marlin by fishery for the main fisheries with weight data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Model estimates are from the model using natural mortality of 0.4 per year, $k = 0.6$, and the uninformative prior on steepness of the SSR. Only weight samples with a minimum of 30 fish per year are plotted.

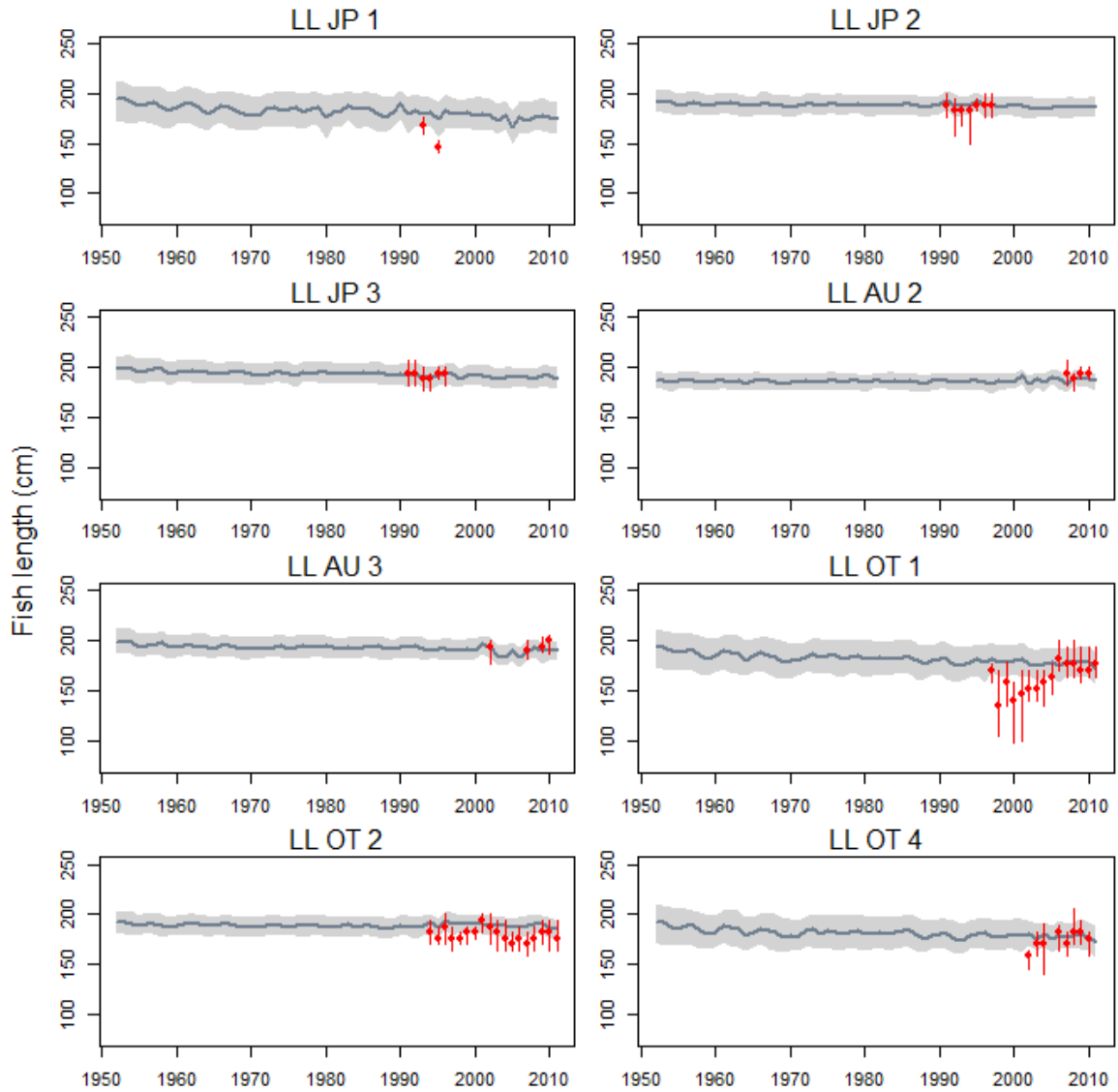


Figure 18. A comparison of the observed (points) and predicted (grey line) annual median length (EFL, cm) of striped marlin by fishery for the main fisheries with length data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Model estimates are from the model using natural mortality of 0.4 per year, $k = 0.6$, and the uninformative prior on steepness of the SSR. Only length samples with a minimum of 30 fish per year are plotted.

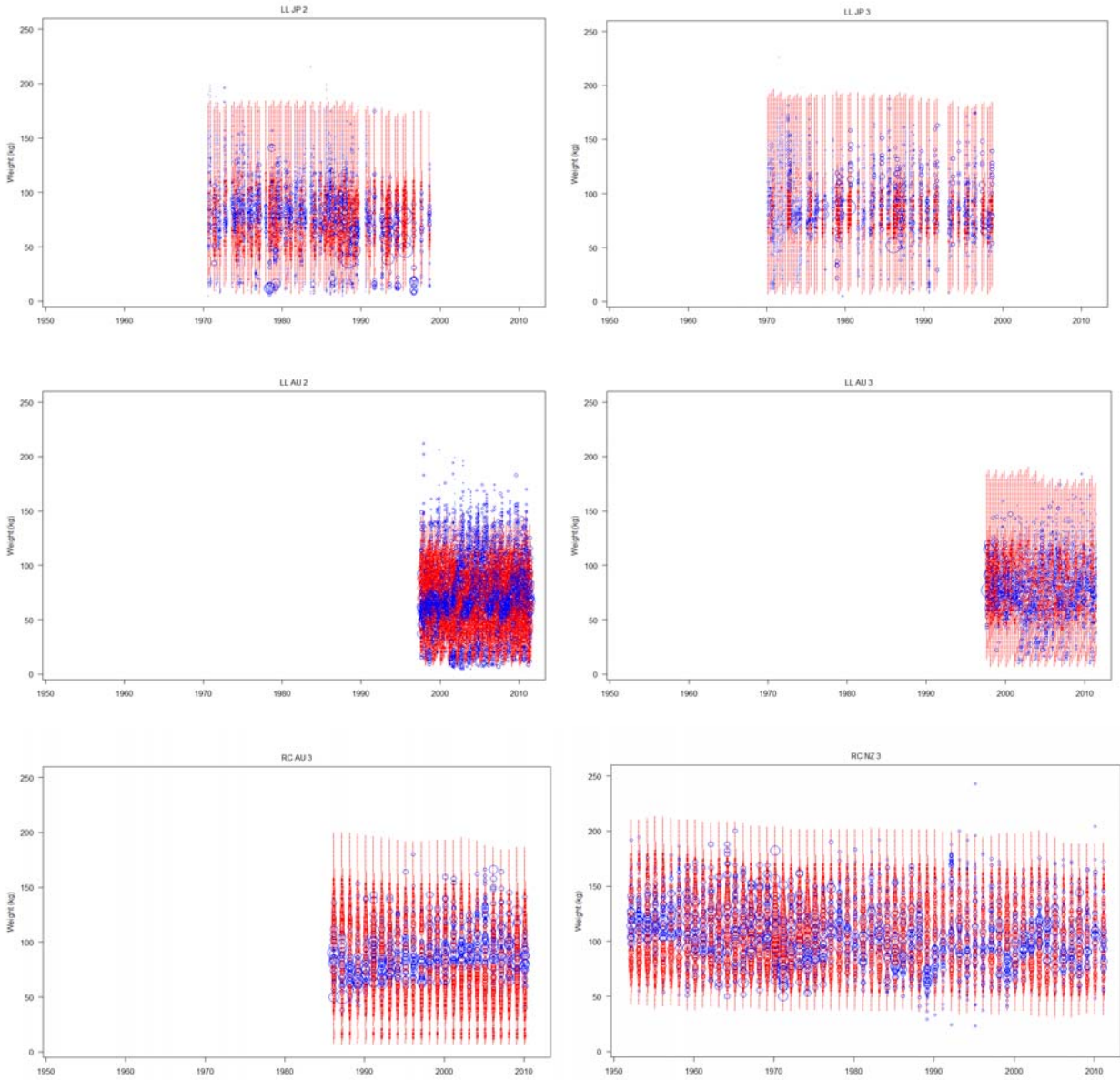


Figure 19. Residual plots of the fit to the weight frequency data for the major longline fisheries for the Ref.case model. Positive residuals (more fish presented than predicted) are shown in blue and negative residuals in red. The diameter of circle is proportional to the square root of the residual.

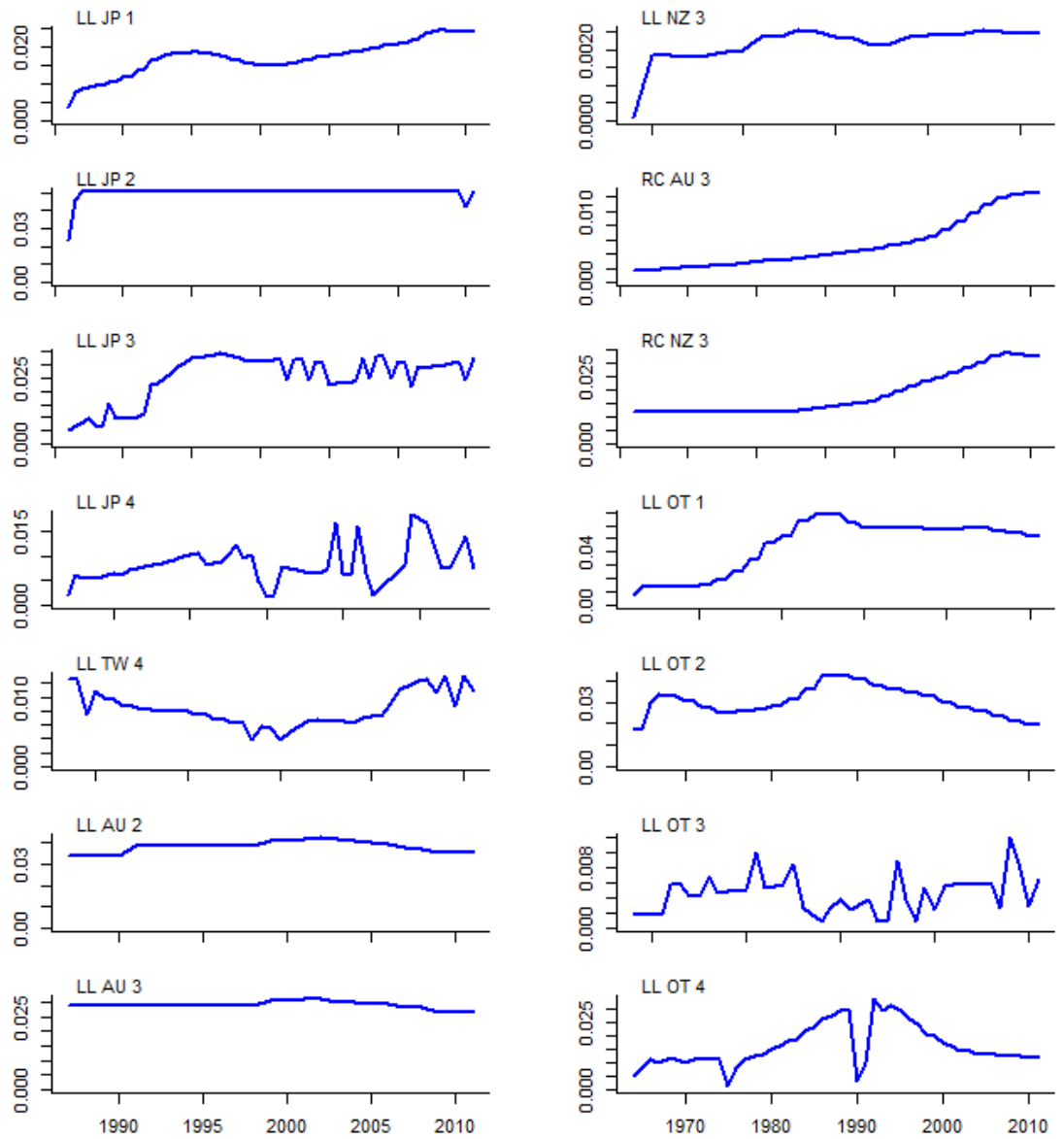


Figure 20. Average annual catchability time series for each fishery in the model region. Model estimates are from the model using natural mortality of 0.4 per year, $k = 0.6$, and the uninformative prior on steepness of the SSR.

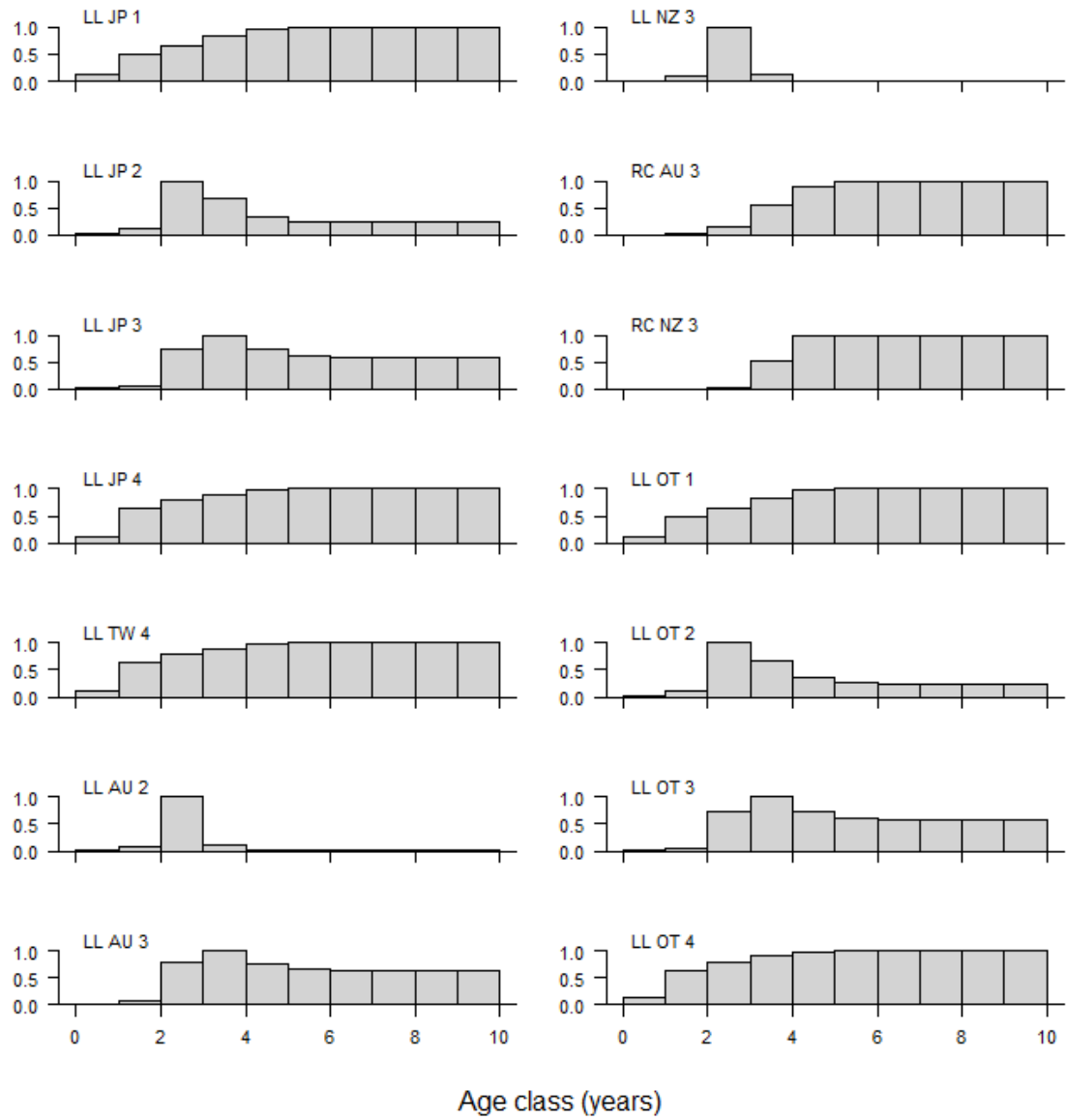


Figure 21. Selectivity coefficients for each fishery in the model region. Model estimates are from the model using natural mortality of 0.4 per year, $k = 0.6$, and the uninformative prior on steepness of the SSR.

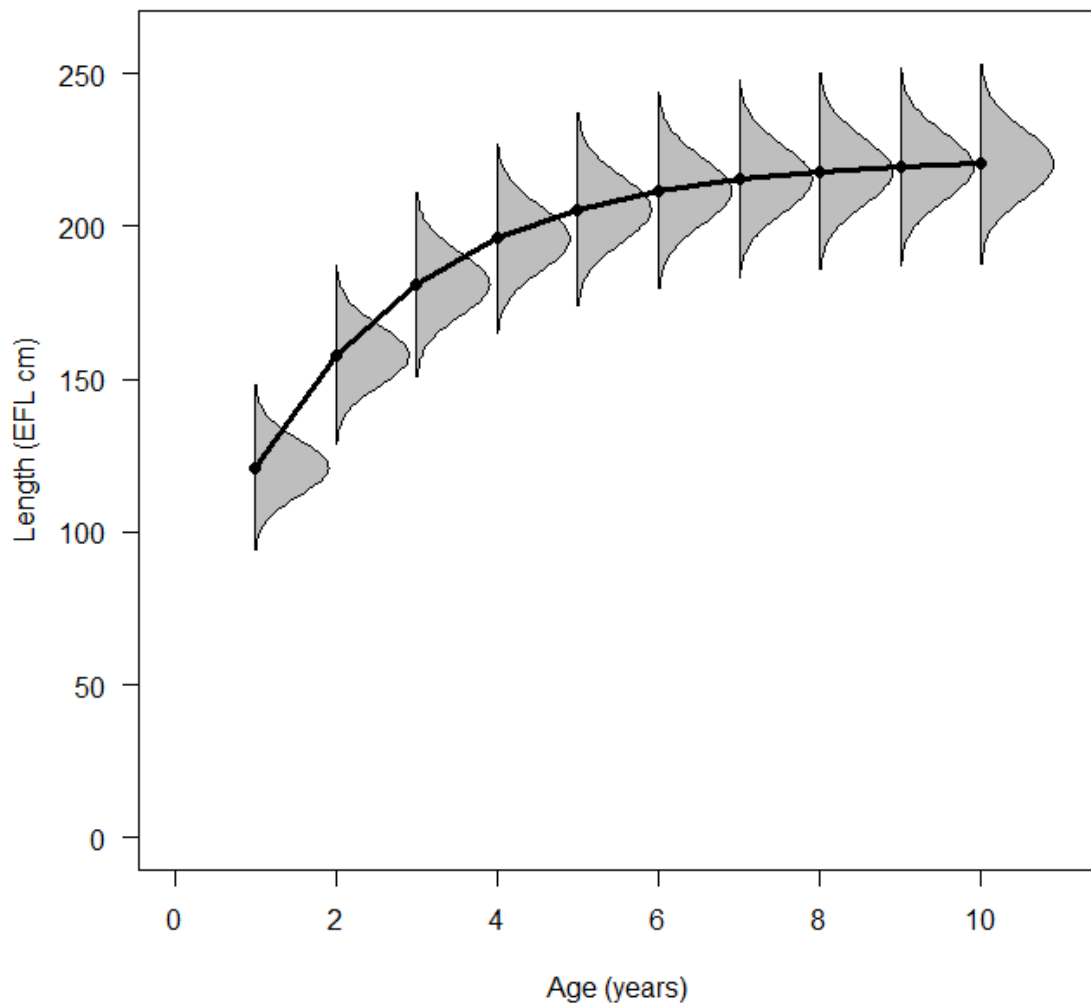


Figure 22. Estimated growth parameters from the striped marlin assessment. The black line represents the estimated length (EFL, cm) at age and the grey area represents the estimated distribution of length at age. The blue points represent observations of age at length from Kopf et al. (2005) converted to the EFL measurement. Model estimates are from the model using natural mortality of 0.4 per year, $k = 0.6$, and the uninformative prior on steepness of the SSR. The green line represents the growth function used in the slower growth sensitivity analysis ($k = 0.3$).

Comparison growth curves (+/- 1sd)

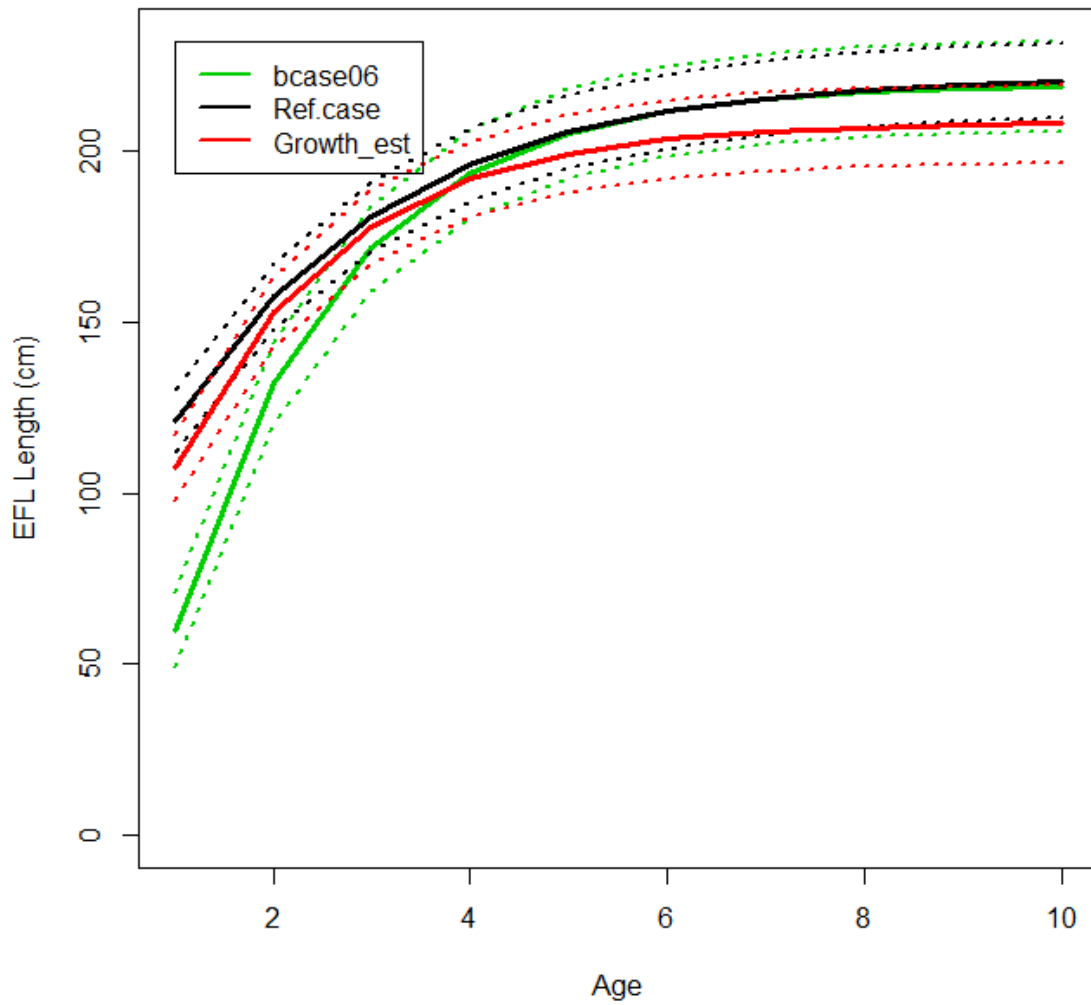


Figure 23: Comparison of the fixed growth curve assumed for the Ref.case model (black) with those estimated for the base case in the 2006 stock assessment (green), and for the sensitivity model (Growth_est) to the 2012 Ref.case (red).

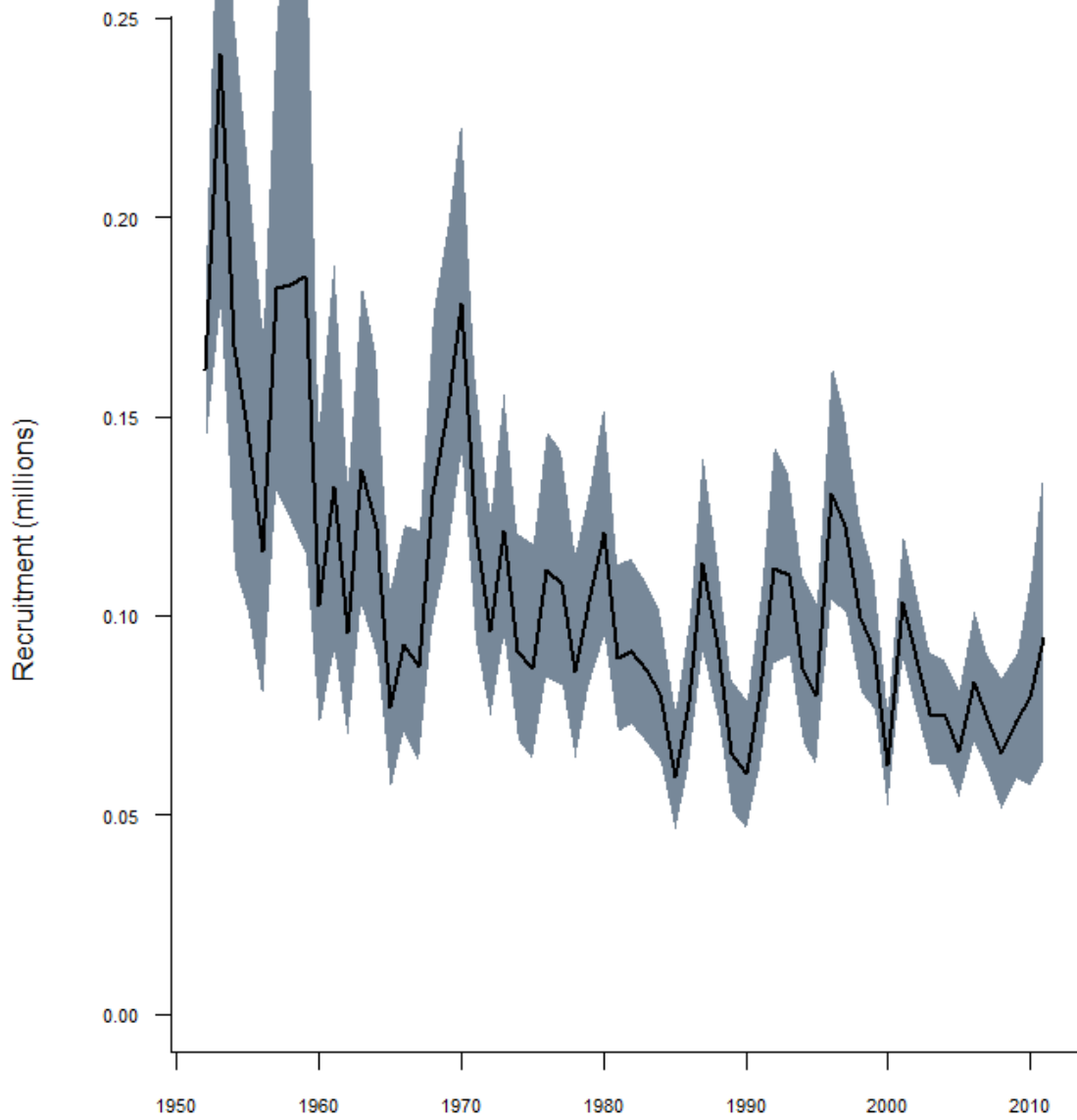


Figure 24. Annual recruitment estimates (number of fish) of striped marlin in the model region. The shaded area indicates the approximate 95% confidence intervals. Model estimates are from the model using natural mortality of 0.4 per year, $k = 0.6$, and the uninformative prior on steepness of the SSR.

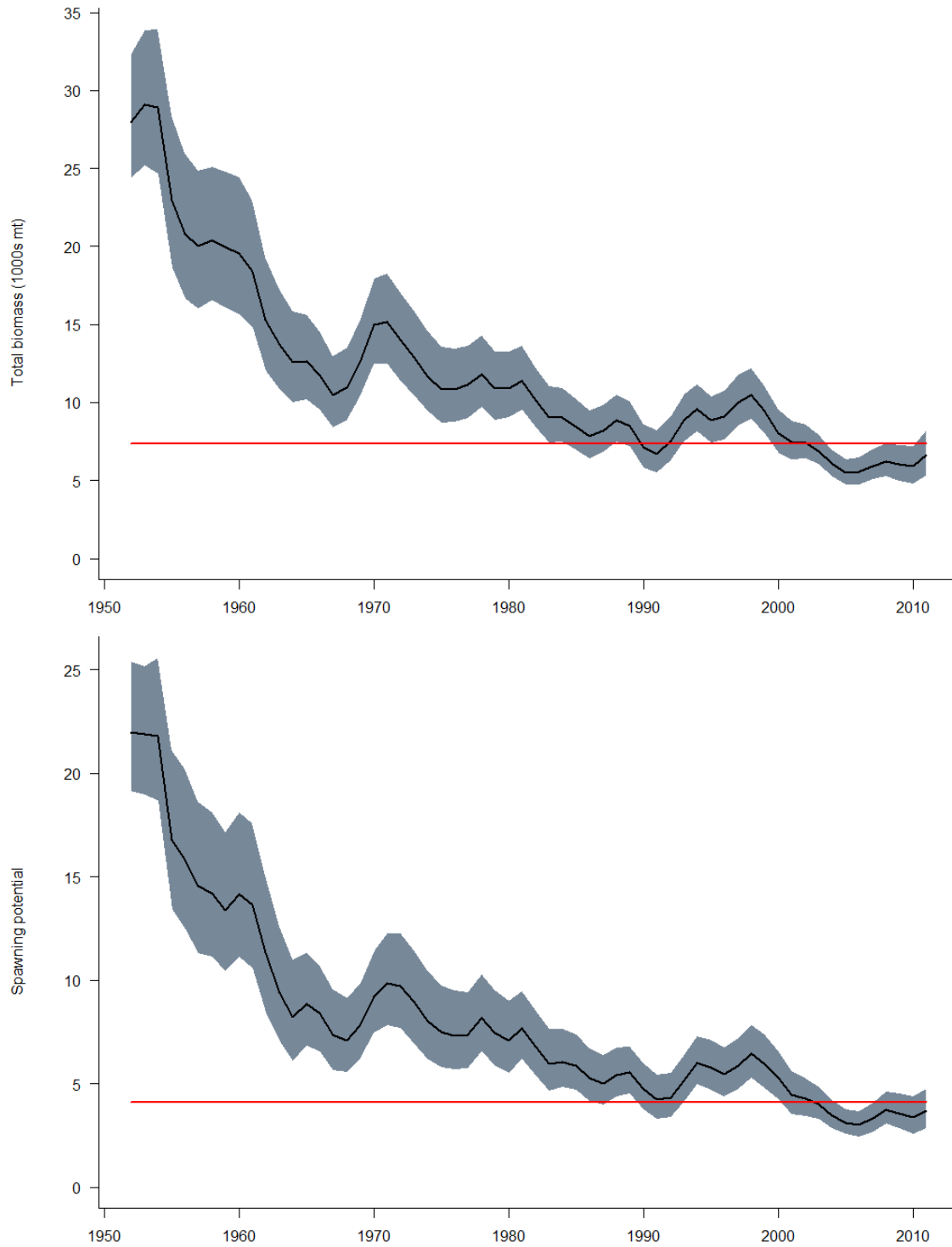


Figure 25. Annual Ref.case model estimates of total (top) and adult (bottom) striped marlin biomass (metric tonnes) in the model region. The shaded area indicates the approximate 95% confidence intervals. The red line indicates the respective MSY levels.

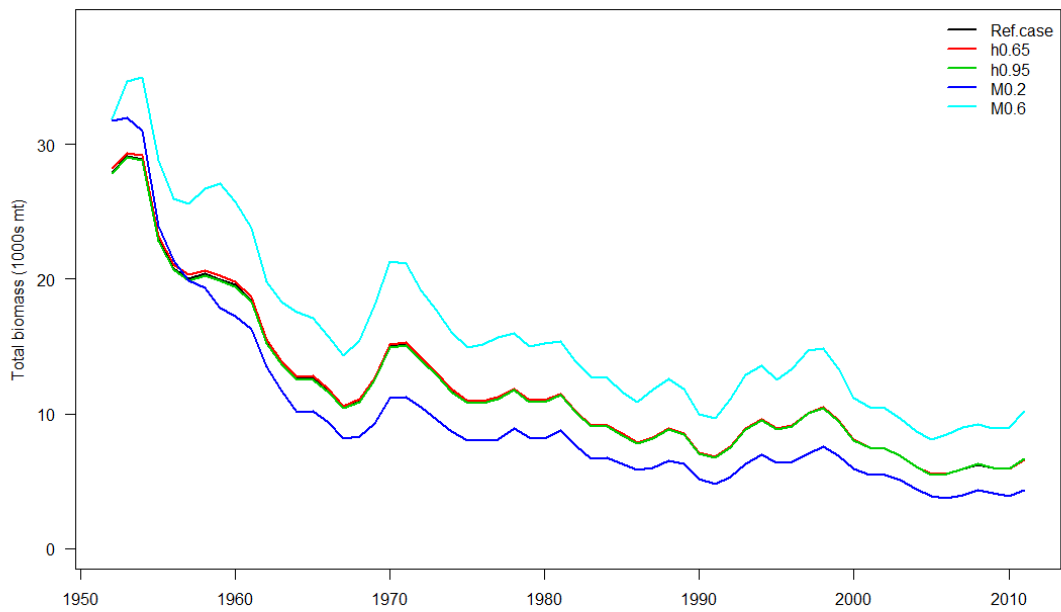
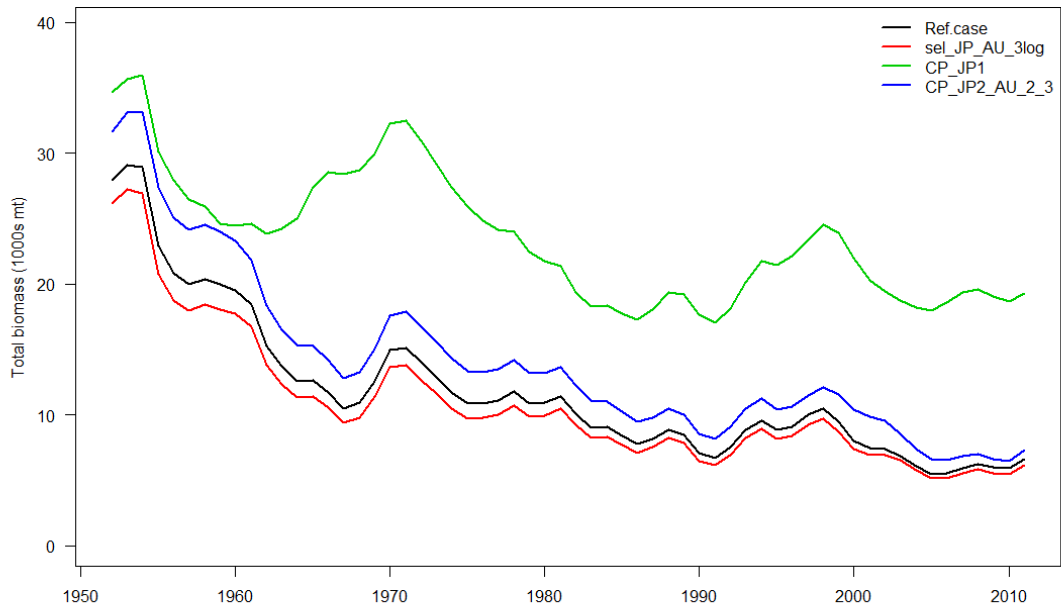


Figure 26: Sensitivity of the Ref.case model to assumptions for selectivity and standardised CPUE indices fitted in the model (top) and to assumed values for steepness and natural mortality (bottom).

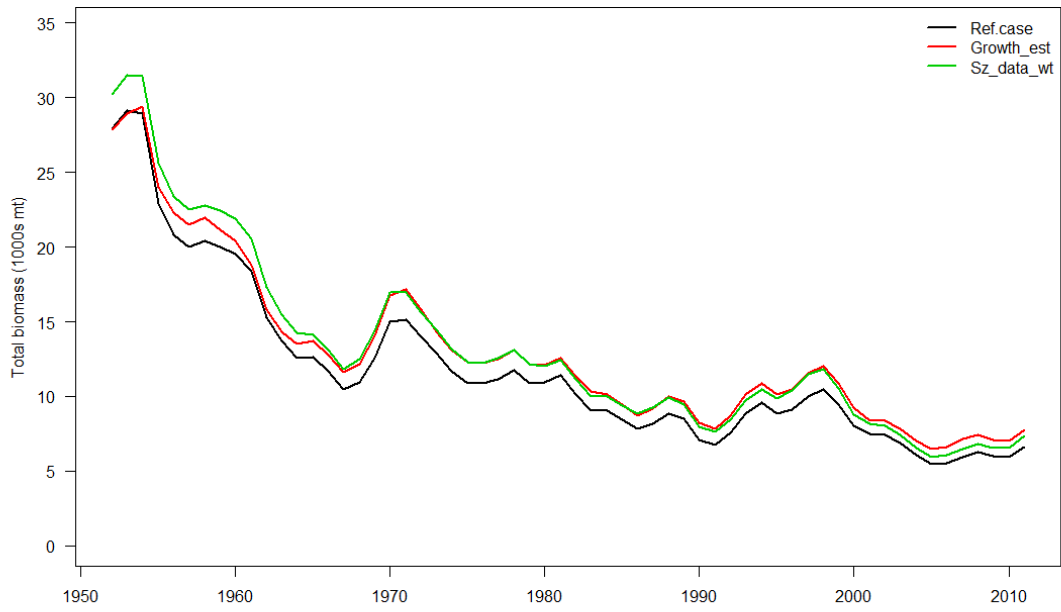


Figure 26 cont.. Sensitivity of the Ref.case model to relative weight of size data assumed in the model fit and to estimating the growth function.

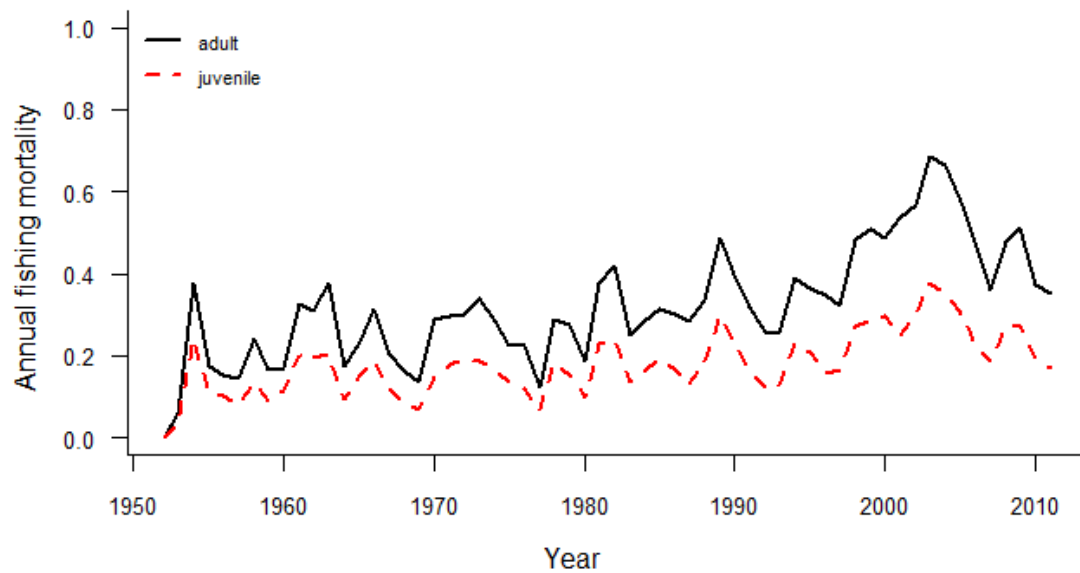


Figure 27. Annual estimates fishing mortality for juvenile (red dashed line) and adult (black line) striped marlin in the model region. Model estimates are from the model using natural mortality of 0.4 per year, $k = 0.6$, and the uninformative prior on steepness of the SSR.

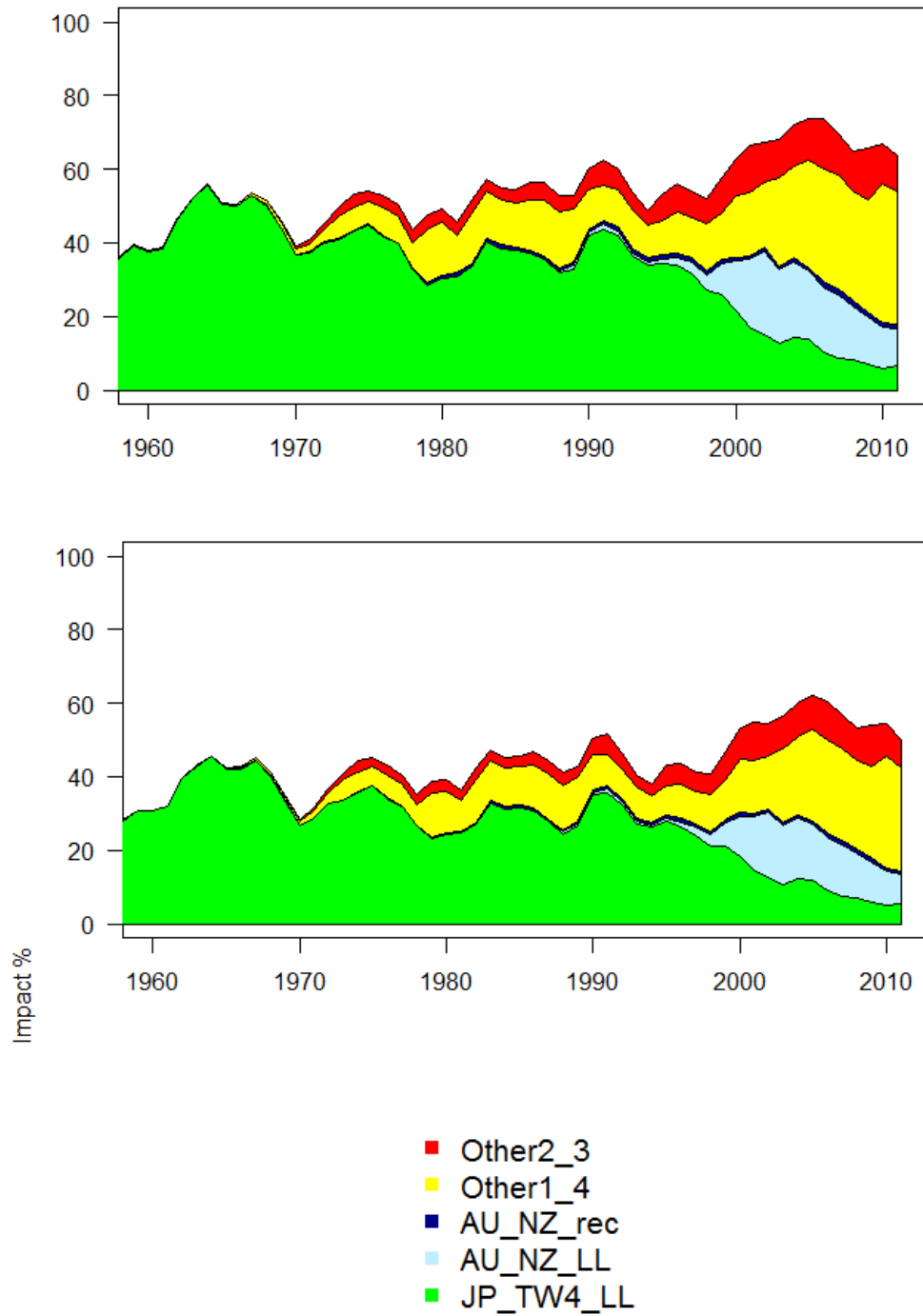


Figure 28. Ref.case model estimates of the reduction in spawning potential (top) and total biomass (bottom) due to fishing (fishery impact $1 - SB_t/SB_{tF=0}$) and attributed to various fishery groups (Ref.case). JP_TW4_LL = all JP longline fisheries and LL TW4; AU_NZ_LL = all AU and NZ longline fisheries; AU_NZ_rec = all AU and NZ recreational fisheries; Other1_4 = LL Other1 & 4; and , Other2_3 = LL Other2 & 3.

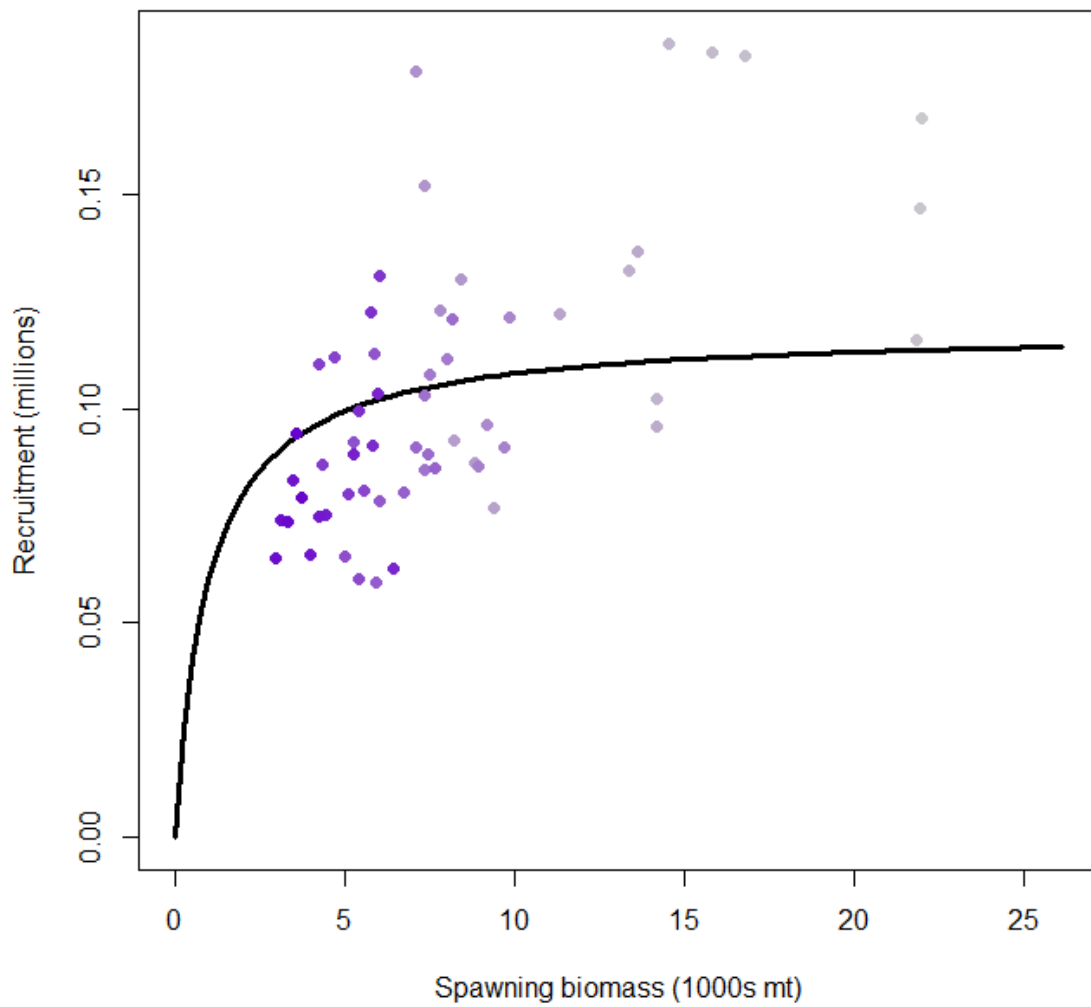


Figure 29. Spawning biomass – recruitment estimates for the Ref.case model and the fitted Beverton and Holt stock-recruitment relationship (SRR) for striped marlin in the model region. Shading of the points from lighter to darker indicates estimates from the early to most recent years.

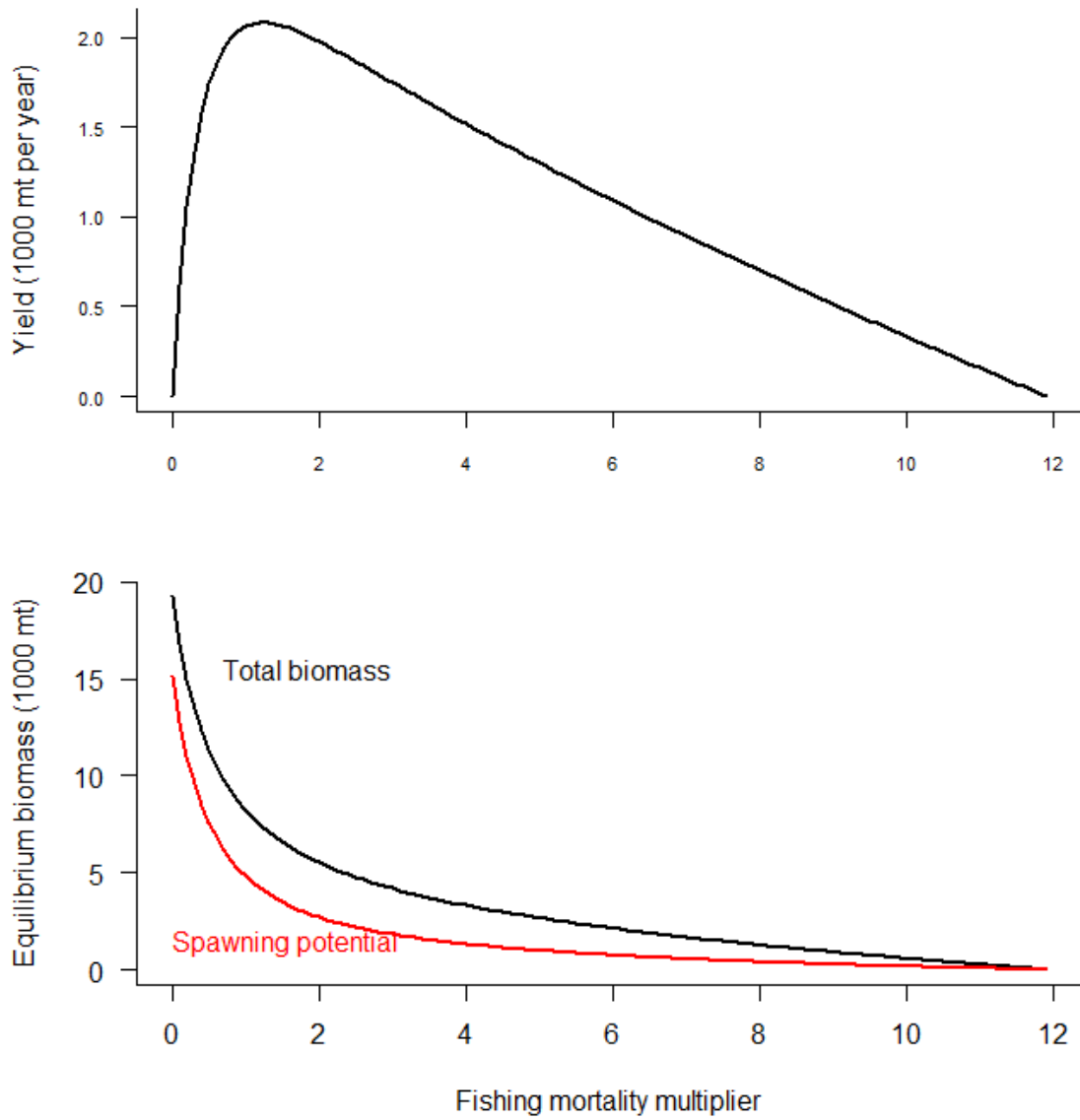


Figure 30. Equilibrium yield (metric tonnes) as a function of fishing mortality multiplier (f_{mult}) for the model using an uninformative prior on steepness and $M = 0.4$. The vertical line represents F_{MSY} . The shaded areas represent approximate 95% confidence intervals.

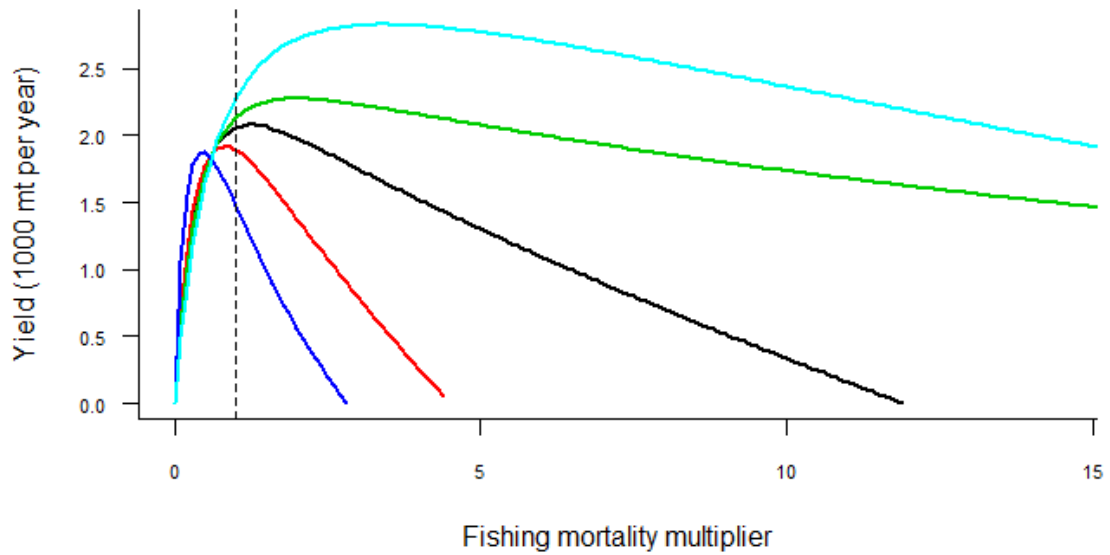
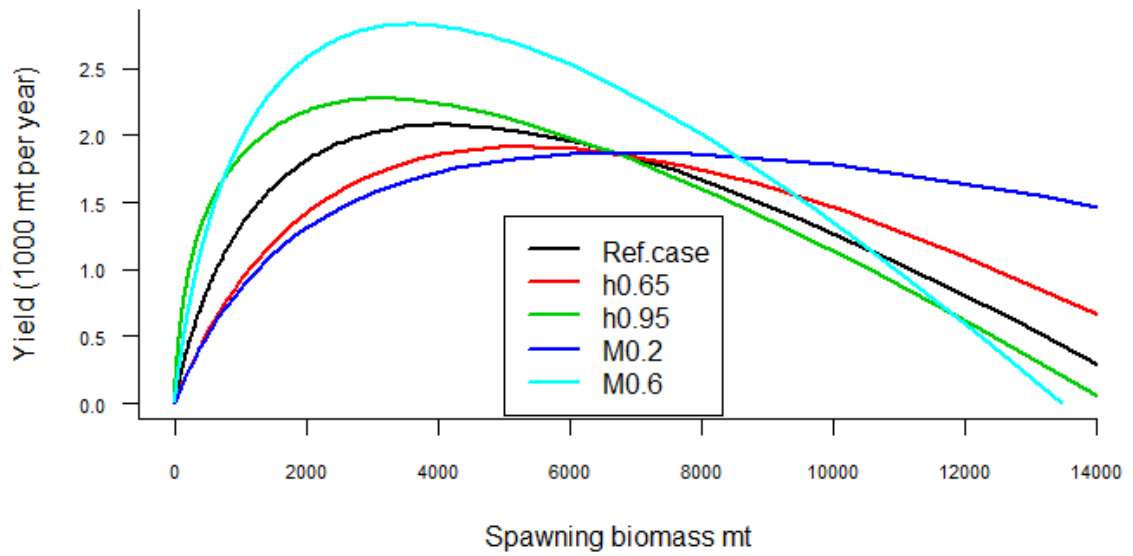


Figure 31. Estimated yields (mt) of striped marlin at different levels of effort under different scenarios of natural mortality, the growth parameter k and steepness of the SRR. The “base case” analysis (low steepness, $M=0.4$) is shown in blue.

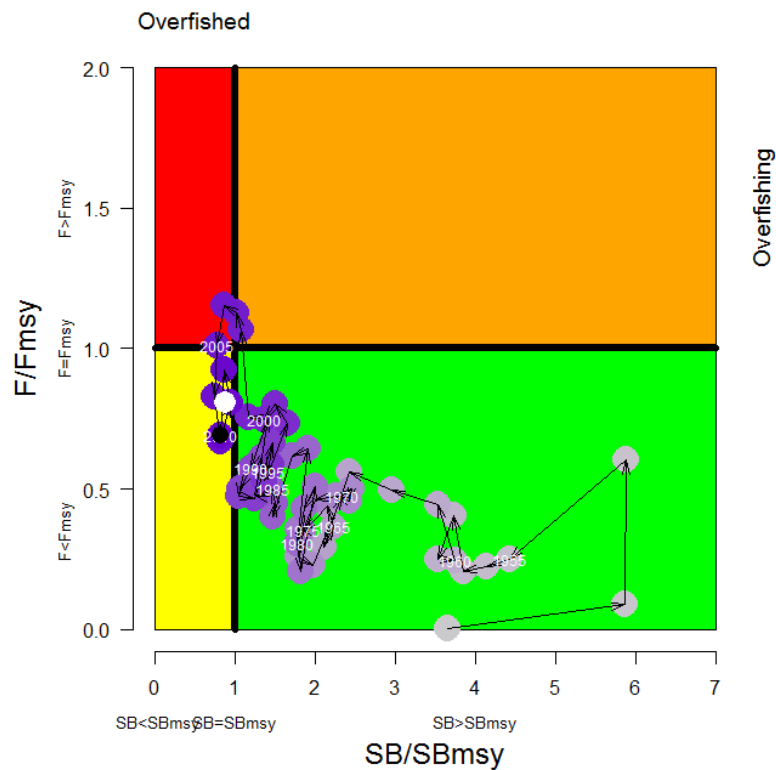
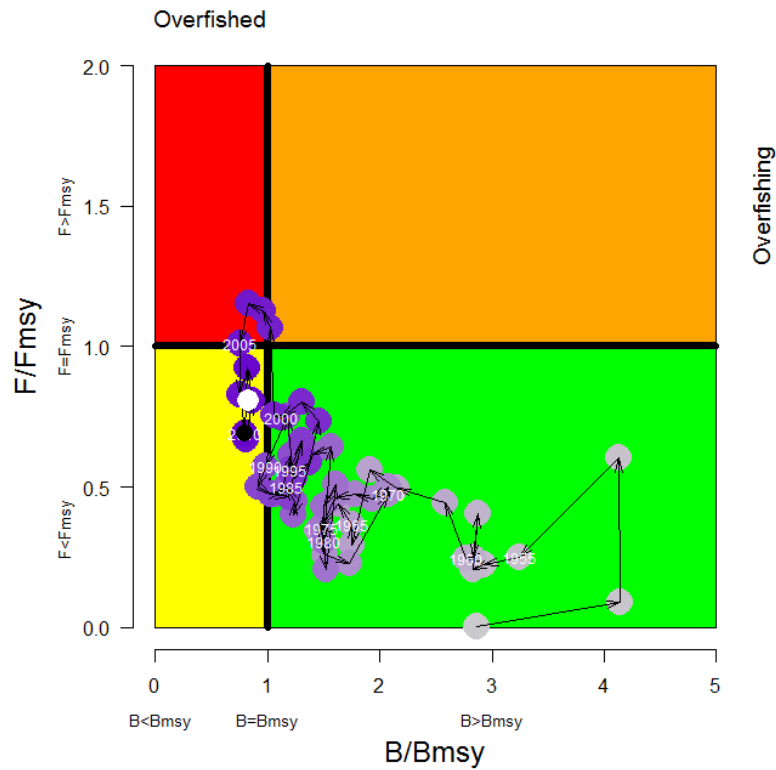


Figure 32. Temporal trend in annual stock status relative to B_{MSY} (x-axis) and F_{MSY} (y-axis) reference points (top), and SB_{MSY} (x-axis) and F_{MSY} (y-axis) (bottom), for the period 1952–2010 (Ref.case). The colour of the points is graduated from mauve (1952) to dark purple (2010) and the points are labelled at 5-year intervals. The white circle represents the average for the period 2007-10 and the black circle the 2010 values.

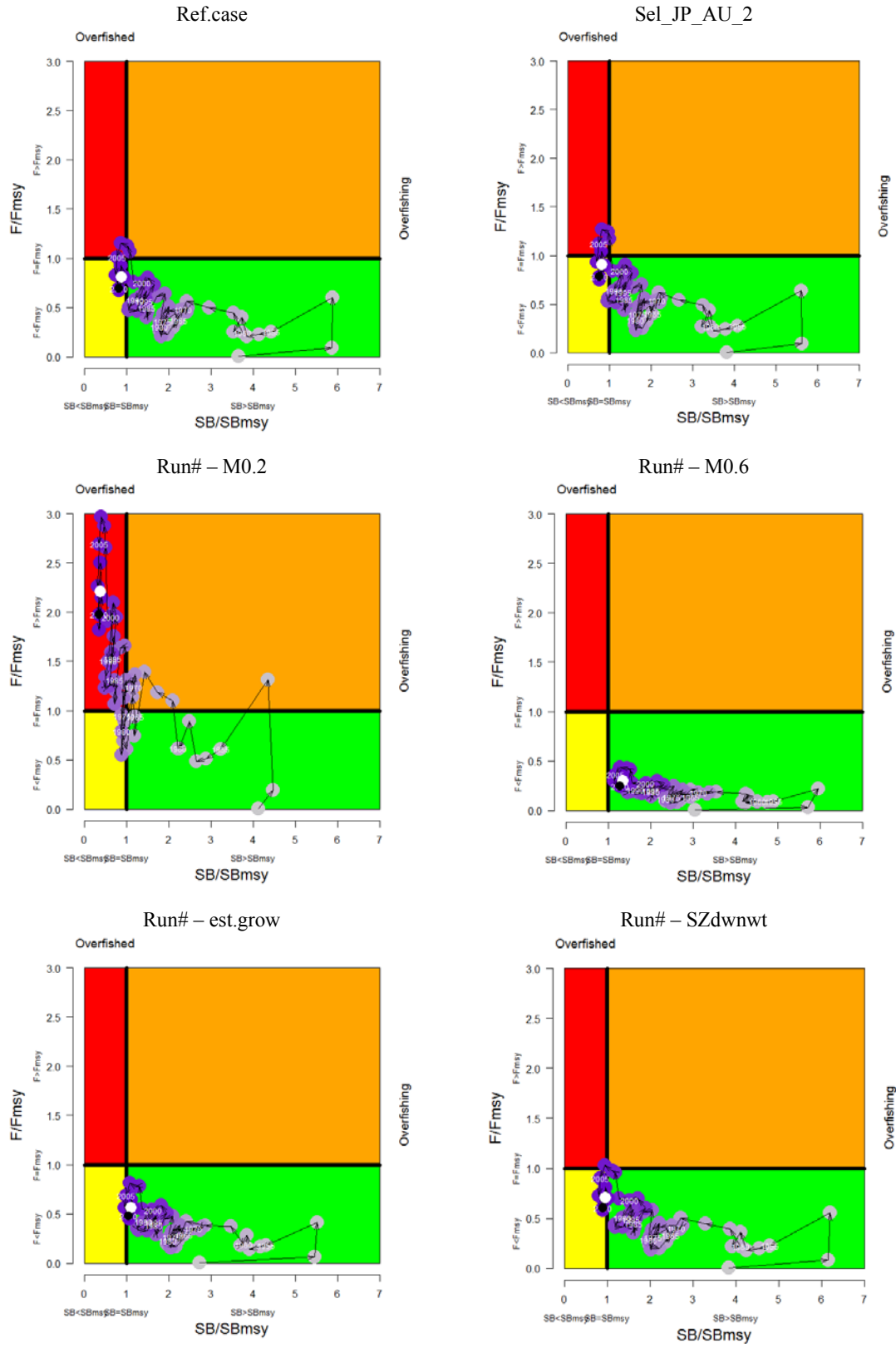


Figure 33. Temporal trend in annual stock status, relative to SB_{MSY} (x-axis) and F_{MSY} (y-axis) reference points for the Ref.case and key model runs.

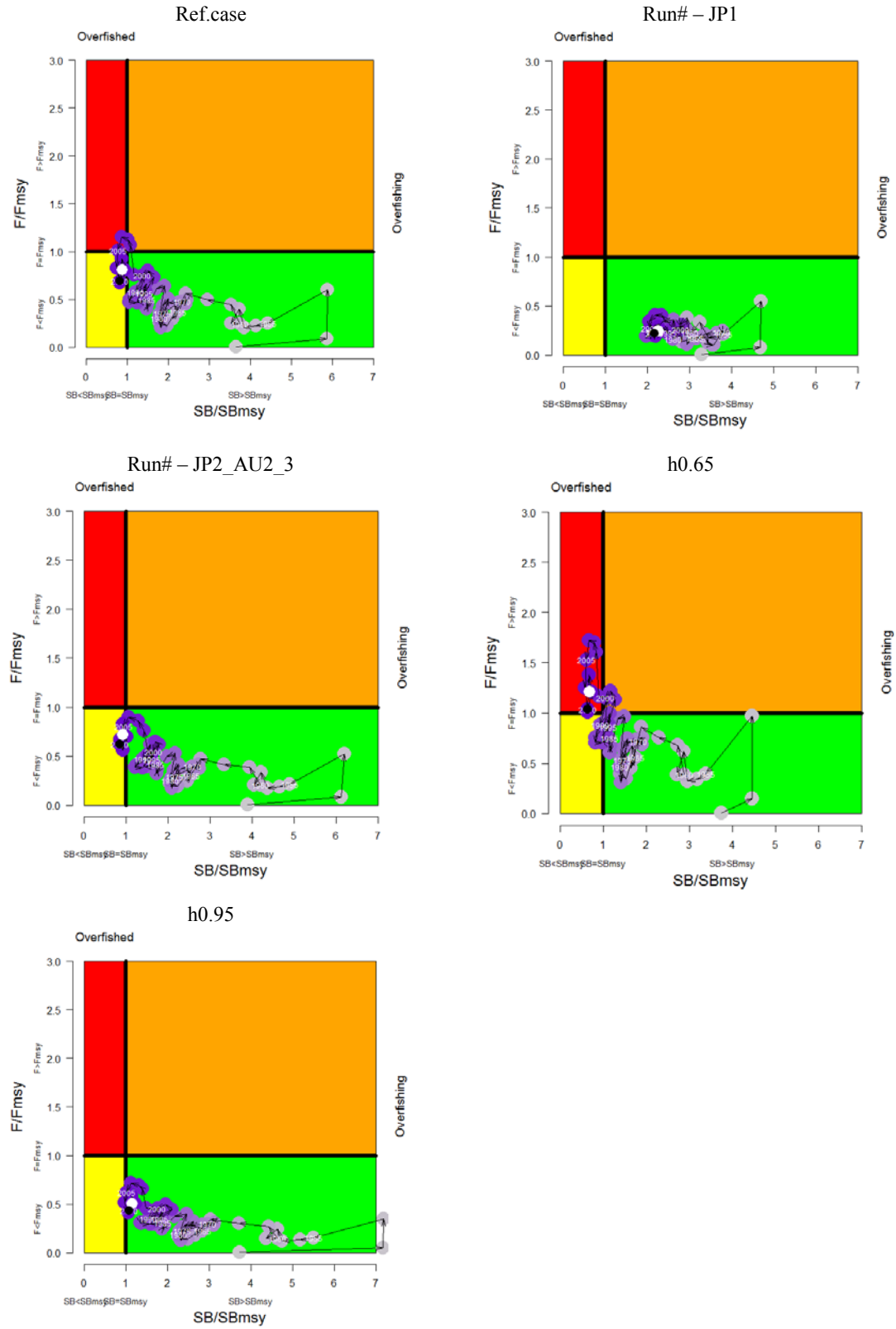


Figure 33. cont. Temporal trend in annual stock status, relative to SB_{MSY} (x-axis) and F_{MSY} (y-axis) reference points for the Ref.case and key model runs.

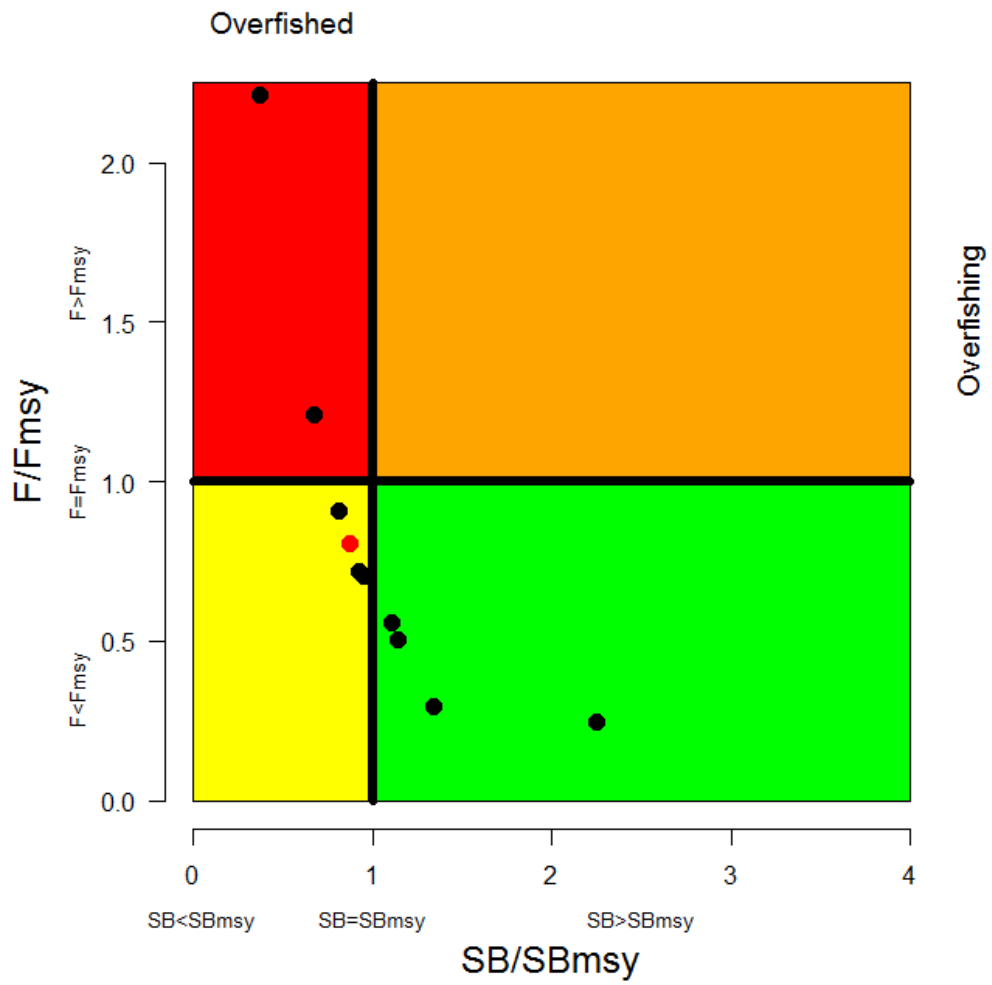


Figure 34. Summary of current stock status (based on 2007-10) for the key model runs. The red circle represents the Ref.case run.

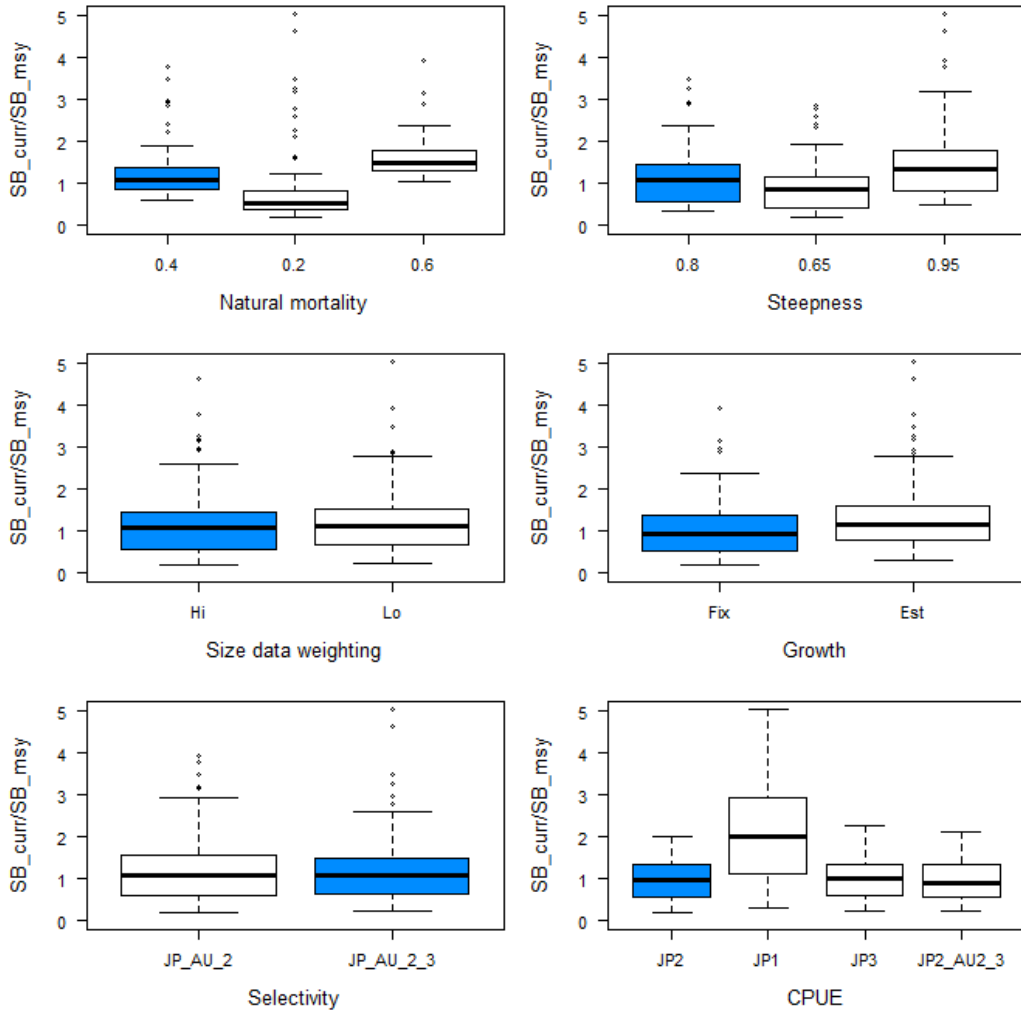


Figure 35. Stock status quantity SB_{curr}/SB_{MSY} with respect to the options investigated in each of the factors included in the uncertainty grid. The options associated with the Ref.case model are in blue.

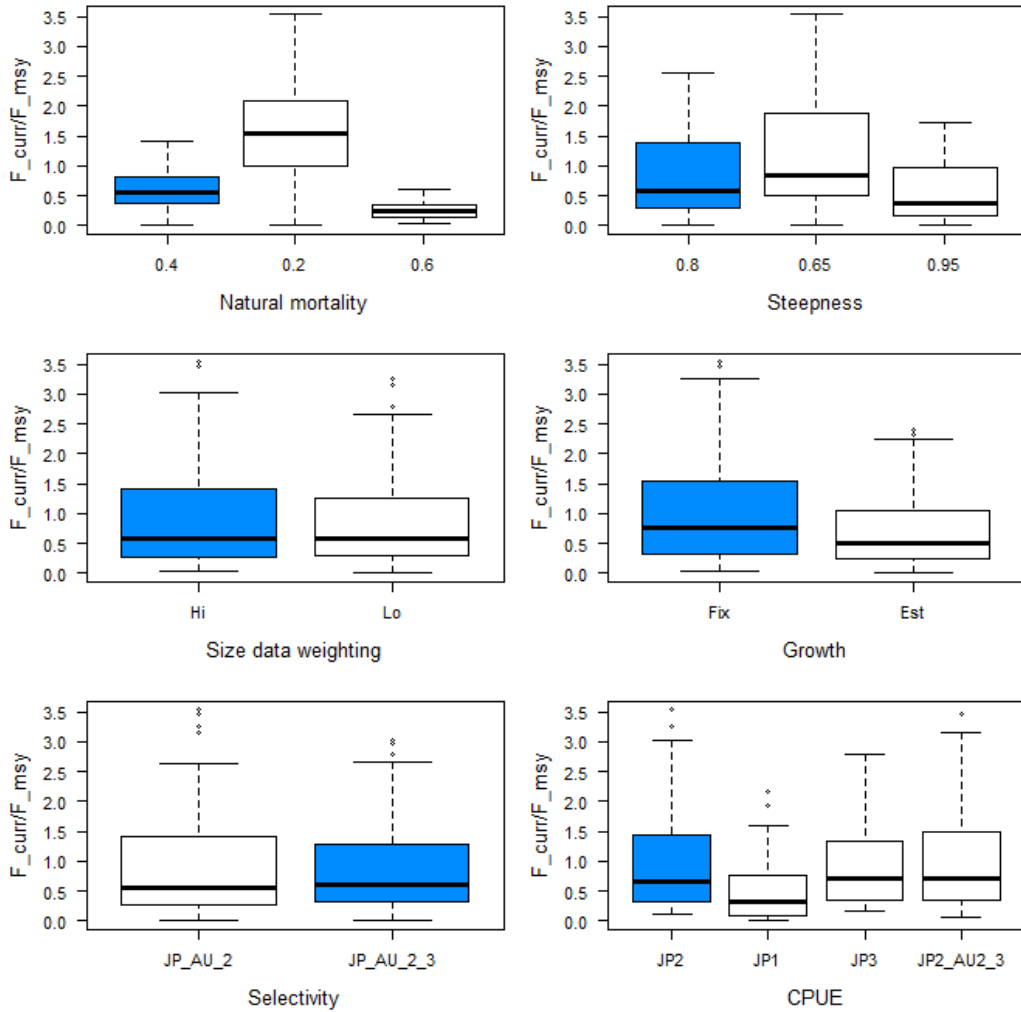


Figure 36. Stock status quantity F_{curr}/F_{MSY} with respect to the options investigated in each of the factors included in the uncertainty grid. The options associated with the Ref.case model are in blue.

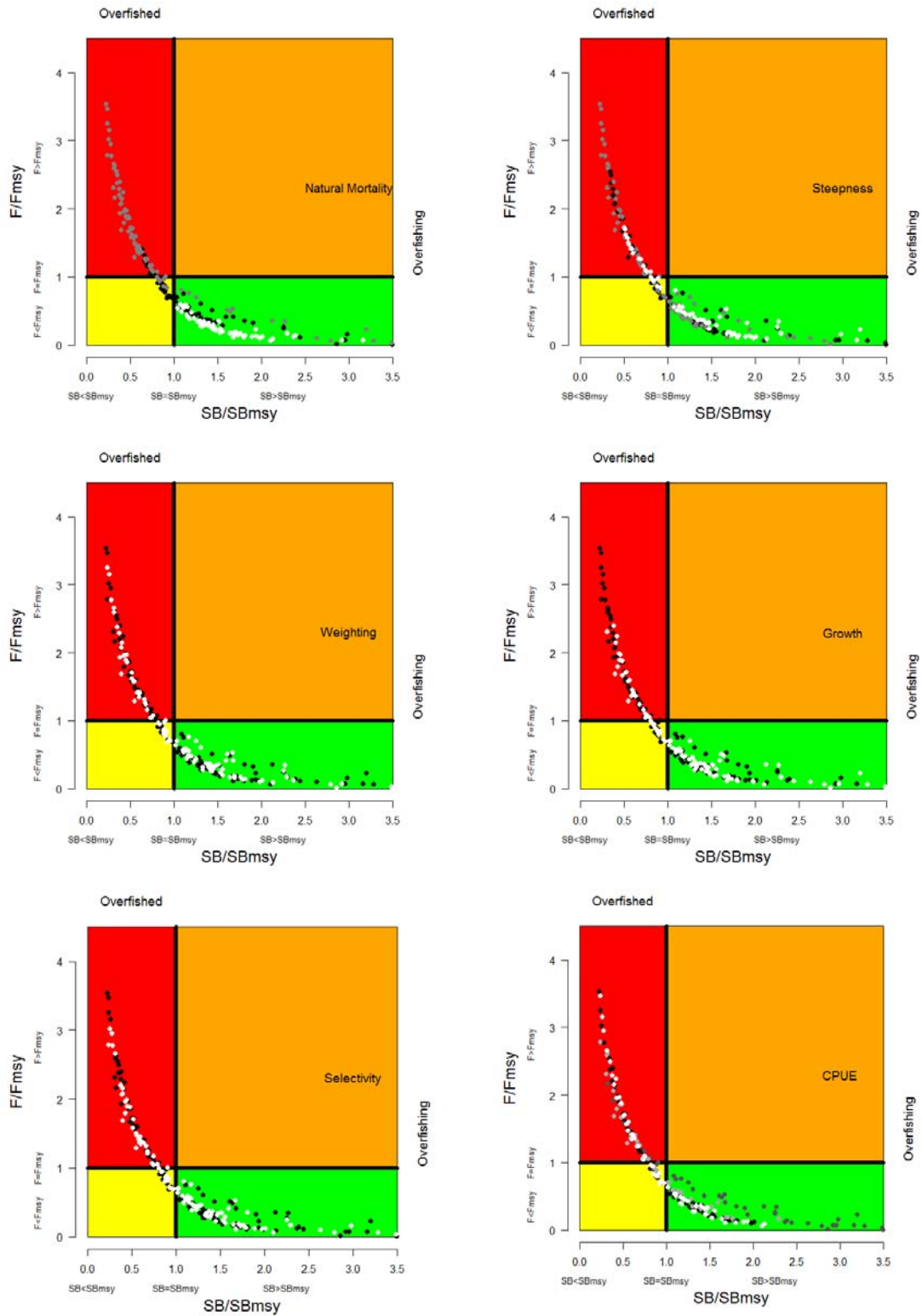


Figure 37. Plot of $SB_{current}/SB_{MSY}$ versus $F_{current}/F_{MSY}$ for the 229 model runs undertaken for the structural uncertainty analysis. The runs reflecting the Ref.case assumption are denoted with black circles while the runs with the alternative assumption are denoted with white circles. For the natural mortality, steepness, and CPUE panels the symbols denote the alternatives in order shown in Table 5 from dark grey to white.