SCIENTIFIC COMMITTEE
NINTH REGULAR SESSION

6-14 August 2013
Pohnpei, Federated States of Micronesia

STOCK ASSESSMENT OF SWORDFISH (*Xiphias gladius*) IN THE SOUTHWEST PACIFIC OCEAN

WCPFC-SC9-2013/SA-WP-05

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Executive summary

This paper presents the 2013 assessment of swordfish in the southwest Pacific Ocean, updating the previous assessment done in 2008. 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 Chinese Taipei longline catch and effort data (Hoyle et al. 2013); standardised CPUE analyses of operational catch and effort data for Australian longline fishery (Campbell 2012); and New Zealand (OFP, 2013), and for the Spanish (i.e. European Union) (OFP, 2012). The assessment includes a new "reference case[2]" model (Ref.case), and then a series of "one-off" sensitivity models that represent a single change from the Ref.case model run. The key model runs were taken as representing a set of plausible model runs, and these were included in a structural uncertainty analysis (grid) for consideration in developing management advice.

The main developments to model structural assumptions were to: assume two model regions, biologically connected, based on the results of recent electronic tagging programmes, and relaxing assumptions such as the relative recruitment to each region; fixing steepness at 0.8; estimating spline and non-decreasing selectivities for the main longline fisheries. A new statistical assumption was to include time-variant precision in fitting the model to standardized CPUE indices. A summary of these and the alternative assumptions for Ref.case and the other key model runs as agreed at a pre-assessment workshop (OFP 2013) are provided below:

Assumption	Ref. case	Sensitivities	
Steepness	0.8	0.65; 0.95	
Movement (diffusion rate)	0.11	0.0; 0.05; 0.25	
Growth rate / maturity / mortality schedule	GHMHS	GHMH GHML GHMLS	GAMHS GAMH GAML GAMLS
CPUE series	Region 1: DW_1C, AU_1 Region 2: DW_2C; EU_2	Region 1: DW_1C, AU_1 Region 2 options: 1. DW_2C only 2. DW_2C, NZ_2	
Size data relative weighting	AU, NZ = nsamp/40; Other = nsamp/100	AU, NZ = nsamp/80; Other = nsamp/200	

Whereas the 2008 assessment was unable to derive reasonable estimates of biomass for the central south Pacific (model region 2), the Ref.case provided reasonable estimates of absolute abundance for the entire model domain. The new data available for region 2 and sufficient consistency among trends in data for the key fisheries may account for the increased certainty possible in this assessment.

Annual recruitment estimates were directly affected by unusual and consistent trends (sustained increases and decreases over time) in the DW_1C CPUE time series. These trends seem unlikely in the case of a by-catch fishery operating during a period of relatively high estimated stock abundance, and are unlikely to reflect a real trend in relative abundance unless the fishery selectivity has varied over time. Unfortunately the limited size frequency samples prohibit the detection of such changes in fish sizes caught over the time series.

The overwhelming source of uncertainty in this assessment is attributable to the assumptions for the growth, maturity and mortality at age schedules. These were taken directly from the 2008 assessment in the absence of new information, and comprise two main schedules, being one derived from Hawai'ian and the other derived from Australian growth estimates. These assumptions dominated the uncertainty estimates derived over the key model runs and from the structural uncertainty analysis. Although other sources of uncertainty in the assessment were identified, e.g.: data conflicts in size and CPUE data;

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[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.

assumed steepness; and lack of fit to some size data, the two groups of growth schedules largely determined the range of the estimates for stock status. Consequently, estimates of stock status have been categorised according to these two schedules.

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 relatively steep decline in biomass over the period 1997 to 2011 over all key model runs, despite the no concurrent temporal change in recruitment, is a notable feature of the current assessment. It is concurrent with large increases in catch particularly in region 2, and declines in CPUE and median fish sizes in the main fisheries. The recent increase in the AU_1 CPUE index is best described by the Ref.case model for which the faster Hawai'ian schedule is made; whereas no increase is predicted when the slower Australian schedule is assumed.
2. Estimates of absolute biomass and equilibrium yield were sensitive to including the NZ_2 standardized CPUE time series in the model fit (key model run cpopt_TW_NZ). The recent declines in the Ref.case model indices for region 2 appear to be consistent with declines in median size over the same period, whereas the NZ_2 index is in conflict with this trend, and is derived from a limited spatial distribution. On this basis, the cpopt_TW_NZ model is considered unreliable, or at least highly uncertain, and this model estimate is excluded from the ranges of the key model runs provided below.
3. The key source of uncertainty in this assessment is the assumed growth/maturity/mortality at age schedule. Estimates of stock status are highly uncertain with respect to this assumption. Across the uncertainty grid, where the Hawai'ian schedule was assumed, the probability of F_current/F_MSY being less than 1 was less than 2%, while where the slower Australian schedule was assumed, this increased to 51%.
4. Total and spawning biomass are estimated to have declined most notably since the late 1990s, with more gradual declines before that time. Current levels of total biomass $B_{current}/B_0$ = 44 – 68 % and spawning biomass $SB_{current}/SB_0$ = 27 - 55% (range of key model runs).
5. 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 current period, spawning potential is at 26 - 60% (range of key model runs) of the level predicted to exist in the absence of fishing while assuming the historical estimated annual recruitments.
6. Recent catches are between 82% of the MSY level and 102% above the MSY level of between 5299 and 12,730 mt (range of key model runs). Within this range,
    - assuming the Hawai'ian schedule produces estimates between 82% of the MSY level and 24% above the MSY level, while,
    - assuming the Australian schedule produces estimates that are between 53 and 102% above the MSY level.

    Based on these results, we conclude that under the Hawai'ian schedule current catches are around the MSY level, while under the Australian schedule current levels of catch are above the MSY level.
7. Fishing mortality for adult and juvenile swordfish is estimated to have increased sharply in the mid 1990s following the significant increases in catches at that time. $F_{current}/F_{MSY}$ was estimated to be between 0.33 and 1.77 (range of key model runs). Within this range:
    - assuming the Hawai'ian schedule produces estimates between 0.40 to 0.70, while,
    - assuming the Australian schedule produces estimates that are between 1.06 to 1.77.

    Based on these results, we conclude that under the Hawai'ian schedule overfishing is not occurring, while under the Australian schedule overfishing is occurring.

8. Current stock status compared to the BMSY-related reference points indicates that the current total and spawning biomass are: $\frac{B_{current}}{B_{MSY}}$ from 1.15 to 1.85 and $\frac{SB_{current}}{SB_{MSY}}$ from 1.15 to 3.53, (range of key model runs). Within this range:
   - assuming the Hawai'ian schedule produces estimates between 1.51 to 1.58, and 1.86 to 2.54, respectively, while,
   - assuming the Australian schedule produces estimates are between 1.15 to 1.37, and 1.15 to 1.80, respectively.

   Under either growth/maturity/mortality schedule, current stock status is predicted to be above the level supporting MSY. Based on these results, we conclude that the stock is not in an overfished state.
9. **Based on these results above, and the recent trend in fishing mortality, we conclude that under the Hawai'ian schedule overfishing is not occurring, but under the Australian schedule, overfishing is occurring, the stock is not in an overfished state.**
10. Other assumptions tested in the key model runs that notably affected the estimates of stock status included: lower steepness equating to higher F_{curr}/F_{MSY} and lower SB_{curr}/SB_{MSY}, and higher steepness producing the opposite effect; and where no movement was assumed, more optimistic estimates of stock status were obtained.

This paper also includes a number of recommendations for future stock assessments of swordfish, including research activities to improve model inputs. Of the recommendations made, the development of improved growth / maturity / mortality schedules at age is the most important to reduce the uncertainty in the estimates of management quantities under the current model.

1. Introduction

Swordfish (*Xiphias gladius*) is one of six species of billfishes commonly reported from commercial longline fisheries within the western and central Pacific Ocean (WCPO) (Molony 2005). Swordfish in south Pacific is an important bycatch species in many domestic and distant water fisheries and has been the focus of recently developing target fisheries in the waters of New Zealand, Australia, and in the high seas of the south Pacific by Spanish flagged longline vessels.

Assessments of the assumed south-west Pacific stock were performed for the south-west Pacific (140E–175°W) using MULTIFAN-CL and CASAL, respectively (Kolody et al (2006) and Davies et al (2006)). The southwest Pacific assessment was updated for SC4 in 2008 (Kolody et al, 2008) using MULTIFAN-CL and a combined southwest Pacific and south-central Pacific assessment performed, while a new CASAL-based assessment was also performed for the south-central Pacific alone (175°W-130°W; Davies et al, 2008). For the southwest Pacific, the assessment indicated that overfishing was not occurring and the stock was not in an overfished state. The stock assessment attempted for swordfish in the south-central Pacific was unable to determine the stock status due to a range of factors including the shortness and lack of contrast in the Spanish longline CPUE series and the conflict between the CPUE series for the Chinese Taipei fleet and other fleets. Overall it was concluded that the available data did not indicate evidence of significant fishery impacts at that time. Combined assessments of the south-west Pacific and south-central Pacific were unsuccessful.

This report details a MULTIFAN-CL assessment of the south-west Pacific swordfish stock using a combined two-region 'south-western' and 'south-central' spatial structure. This represents a significant modification of the assessment undertaken by Kolody et al. (2008). Key changes include the refinement of the geographical regions used within the model, based upon the results of recent electronic tagging programmes. Substantial new information has also been added to the assessment. The model now includes five standardised CPUE indices for longline fisheries, including new information from the Spanish fleet in the south-central region. 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 Kolody et al. (2008) since much of the fisheries and biological information remains relevant.

2. Background

2.1. Biology

Swordfish are one of the most widely distributed pelagic species, distributed globally, and observed from 50°N to 50°S and at all longitudes in the Pacific Ocean. Japanese longline catch rate distributions suggest three large, relatively high density areas, the North-West, South-West and Eastern Pacific. In contrast, spawning distributions (as inferred from larval surveys, Nishikawa et al, 1985, and maturity studies, e.g. Young and Drake 2002, Mejuto et al. 2008a) tend to suggest spawning only in tropical and sub-tropical areas, though with conspicuous absence from the Western Pacific equatorial region, and the coastal regions of North and South America. The degree to which individuals migrate and sub-populations mix potentially has important implications for fisheries management, but the effective stock structure is poorly understood. Genetic studies indicate that there is not uniform gene flow among Pacific swordfish populations. Reeb et al (2000) suggest a broad "⊃"-shaped connectivity pattern, such that the SW and NW Pacific populations are the most distinct from each other, with central and eastern populations intermediate between the two. Alvarado Bremer et al (2006) concluded that the SE Pacific population was genetically distinct from the NE and SW. There was additional evidence to suggest that the south-central Pacific represented a population intermediate between the SW and SE, but it was recognized that sample sizes in the south-central region were not sufficient to be conclusive.

In recent years, PSAT and opportunistic conventional tagging programs in the SWP have begun to provide direct information about the movement of individuals (Karen Evans and Chris Wilcox, CSIRO, pers. comm.; Holdsworth et al, 2007; Kolody and Davies, 2008). Tagging seems to confirm that swordfish undergo directed seasonal migrations between temperate foraging grounds and tropical spawning grounds, but it remains unclear how much site fidelity individuals maintain between these migrations. The large-scale collaboration on swordfish electronic tagging in the South Pacific (Evans et al, 2012) has provided new information, which is discussed in Section 2.3.

Swordfish are sexually dimorphic (females growth larger and faster than males) and seem to have different spatial distributions (e.g. Young and Drake, 2002; Mejuto et al, 2008a). Potential sexual differences in other life history characteristics are largely unknown (e.g. migration patterns, natural mortality, etc.).

There have been a number of studies on swordfish growth rates and maturity in the SW Pacific (e.g. Young and Drake 2002, 2004; DeMartini et al. 2000, 2007; Mejuto et al. 2008a; Valeiras et al. 2008). However, recent comparative work on the methods used among laboratories has suggested that there remains a large degree of uncertainty about some of the basic biological characteristics of this species (Young et al. 2008). This is discussed further in Section 4.3.

2.2. Fisheries

Historically, the majority of swordfish catches represented bycatch from the tuna target fisheries; a significant amount of recent catches remains a non-target bycatch. Across the two regions within this assessment, catches slowly increased from the early 1970s up until around 2000, caught primarily by Japanese fleets. Catch levels increased rapidly from the mid-1990s, as more targeted Australian (south-west Pacific Ocean) and New Zealand fisheries developed (south central Pacific Ocean). Japanese catches in the south central region also increased markedly, but generally declined in the south-west. After the year 2000, increasing catches were also taken by the Spanish and Chinese fleets in the south central Pacific Ocean (Figure 1). In the current century, the majority of the swordfish catch has been in the south central Pacific Ocean, particularly following declines in the Australian fishery from the early 2000s.

2.3. Tagging data

A summary of the most recent swordfish tagging data was provided by Harley et al. (2012).

A large-scale collaboration on swordfish electronic tagging in the South Pacific was described in Evans et al. (2012). This programme provided over 50 electronic tag tracks with durations of greater than 30 days. The data indicated that, in combination with long duration conventional recoveries, a division of the stock into south-western and south-central regions (west and east of 175°W), as in the 2008 assessment, was not defensible on biological grounds. Significant differences in behavior were found between fish tagged in the Tasman Sea and those tagged in the south Pacific Ocean to the east of New Zealand. Movement patterns across the Tasman and Coral Seas suggest limited mixing or the partial overlap of sub-populations that may not mix strongly on the spawning grounds. There appeared to be no mixing between the southern and northern WCPO, nor the WCPO and the eastern Pacific Ocean.

While the electronic tagging data in particular were useful in consideration of the appropriate regional structure for the model, the tagging data from the swordfish fishery have limited direct application in the current assessment procedure.

3. Spatial structure, data sources and compilation

The total catch (in numbers) and size composition data for most fleets were provided from the SPC database. Analyses involving effort standardization of Japanese, Australian and New Zealand fleets were conducted with additional fine-scale data with the cooperation of individuals from the respective countries. The following briefly overviews the assessment data used in 2013. Much more detailed summaries and analyses of the catch, effort and size composition data were provided in Campbell (2008), and catch rate standardization analyses are detailed in Campbell et al. (2012) and Hoyle et al. (2013).

Data used in the swordfish 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 overall model area for the assessment of the swordfish stock is consistent with the two-region assessment attempted by Kolody et al. (2008), based upon the spatial distribution of catches in the southerly WCPFC region. As in that assessment, this geographic area is divided into two model regions representing the south-west and south-central. However, the division between these two regions was adjusted based upon the latest information from the tagging analysis by Evans et al (2012), which indicated that the swordfish stock assessment should consider two regions in the Southern Hemisphere. The western region was suggested to extend from the Australian coast to 165°E, and the eastern region from 165°E to 130°W (the eastern WCPFC convention boundary). This structure, with an expanded south-central Pacific region, was used to revise the model structure and fishery definitions. Each model region was also divided into three sub-areas to aid fishery definition: a northern, central and southern fishery sub-area (Figure 2).

3.2. Temporal stratification

Data used in the current analyses covered the period 1952–2011, and excludes 2012 because standardized CPUE indices were not available for all fleets in this year. Given the seasonal patterns of catch and effort within fleets, the model was implemented with a quarterly time step.

3.3. Definition of fisheries

The fishery sub-areas of the model regions were applied to define the spatial boundaries of the specific fisheries in the southwest Pacific Ocean. A total of 14 longline fisheries were defined (Table 1), based on sub-area boundaries, nationality, and time period.

Distant water fishing nation longline fleets, primarily Japanese, have dominated the catches of swordfish, taken primarily as a bycatch. These fleets were grouped together for each fishery sub-area of the two model regions (Fisheries 1-3 and 7-10). The pattern of Chinese, Chinese Taipei, Korean, and Japanese catches by fishery sub-area is shown in Figure 4.

Since the early 1990s, major longline fisheries have also developed in Australia (one fishery across the three sub-areas in region 1, Fishery 4) and New Zealand (one fishery in sub-areas 2c and 2s in region 2, Fishery 11), as well as the more recently developed Spanish fleet (two fisheries across the three sub-areas in regions 1 and 2, Fishery 5 and 12).

Three additional longline fisheries were defined to account for the other sources of longline effort and catch, one in region 1 (across all three sub-areas, Fishery 6) and two in region 2 (in sub-area 2c and 2s, respectively, Fisheries 13 and 14, Table 1). These other longline fisheries included effort and catches by recently developed longline fisheries of PICTs, and the Australian fleet in region 2.

3.4. Catch and effort data

For all fisheries, catch data were expressed as the number of swordfish captured (Table 1) and fishing effort as the number of hooks set. 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. Compared to the 2008 assessment, new data sets were available for the Spanish fleet and Chinese Taipei aggregated data was available stratified according to target species (Hoyle et al. 2013).

For each group of fisheries, we describe the patterns in catch and effort, and where appropriate, the standardised CPUE time series developed to inform the assessment.

Distant water fishing nation longline fisheries (Fisheries 1-3 and 7-10): the distant water fishery was primarily comprised of vessels from the fleets of Japan, China, Korea and Chinese Taipei. This fleet fished in both regions 1 and 2, primarily in the central and northern fishery sub-areas of these regions (Figure 4). Swordfish catches (in numbers) within the Japanese fleet were highest in sub-area 1C up until the mid-1990s, after which catches subsequently declined. The Korean fleet operated primarily in sub-area 2N from the mid 1970s to the early 2000s, after which catches of this fleet declined in that fishery sub-area. Key Chinese Taipei fleet catches were in sub-areas 2N and 2C from the 1970s, but increased particularly from the late 1990s, catches subsequently declining from the mid-2000s, particularly in sub-area 2C. Chinese fleet catches increased rapidly from 2001 in sub-area 2N in particular, peaking at over 40,000 individuals by the late 2000s.

From these data, two key standardised CPUE series were derived from the Japanese and Chinese Taipei fleets:

- Distant-water fishery CPUE in sub-area 1C: 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 data offers the longest time series of CPUE trends for swordfish. Fishing effort by the Distant-water fleet (Fishery 2) were standardised using a generalised linear model (GLM) approach (Hoyle et al. 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). In sub-area 1C, swordfish CPUE was relatively high between 1970 and the late 1990s, subsequently declined to the mid-2000s and then increased but did not reach the previous high levels (Figure 5).

- Distant-water fishery CPUE in sub-area 2C: data from the Chinese Taipei fleet was available from the late 1960s. 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. These data were stratified according to target species and subsequent GLM analysis indicated a change in vessel targeting around 2001. Despite attempts to standardise for this targeting change, there was an abrupt change in standardised swordfish CPUE in 2001. Therefore two separate standardised time series were developed, for the period pre- and post-2001. Unique catchability is assumed for each fishery component. The resulting catch rate time series was relatively stable until the early 2000s (evident in the pre-2001 index), and then declined (post-2001 index).

Australian fisheries (Fisheries 4 and 13/14): following relatively low catches within this fishery in region 1, catches in the central sub-area (1C) increased significantly to over 30,000 individuals per year from the late 1990s to early 2000s, and subsequently declined to below 20,000 individuals by the end of the time series. Notable catches were also taken in sub-area 2C between the early to late 2000s. Those catches were included in fishery 14.

- Australian fishery CPUE in region 1: A CPUE index for swordfish caught by vessels operating within the longline sector of the Australian Eastern Tuna and Billfish Fishery (ETBF, Fishery 4 in region 1) has been updated to 2011 (Campbell, 2012 - SC8-SA-IP13). The time-series of data begins in mid-1997 when logbooks began collecting information on the gear settings used in the ETBF and continues to the end of 2011. Standardised CPUE indices (with catch being the sum of retained and discarded fish) are calculated for three different size classes of fish (Small, Prime and Large) as well as an index for all sizes classes combined. Retained catch for each trip is apportioned to each size class using size data (individual weight data) collected from processors receiving fish landed in the fishery while discards are apportioned based on observer data. Size data for swordfish have been collected for around 80% of all retained fish. The CPUE was standardised by fitting both a binomial model to the probability of attaining a catch (with a logit link) and a negative-binomial model to the size of the positive catch (with a log link) and then combining the two results. The main effects in both models consisted of year, quarter, area (7), hooks-per-hook, bait-type, start-time, percentage of hooks with lightsticks as well as several environmental effects (including moon-phase, sea-surface temperature, mixed-layer-depth, sea-height, wind-speed) together with two additional effects which account for competition between vessels within each 1-degree square. All effects except moon-phase were fitted as categorical variables with the Year, Quarter and Area effects fitted as either a full 3-way interaction or the sum of both Year*Quarter and Quarter*Area interactions with the latter chosen for the final index. Time-variant precision of the index for the combined size class was obtained from the component of the model fitted to the positive catch only. The index was rescaled to have a mean of 1 over the period 97-3 to 11-4.The standardised index displays a steady decline between 1997 and 2003 after which the index increases to 2007 then remains relatively flat through to the end of 2011. A more complete description of this work was provided to SC8 (see SC8-SA-IP13). The resulting CPUE indices are presented in Figure 5 with the time-variant precision estimates in Figure 6.

New Zealand domestic fishery (Fishery 11): Catch from this fishery, in both numbers and tonnes of swordfish, were provided by the Ministry of Fisheries (MFish), New Zealand, for the period 1993–2011.

Major New Zealand catches were in sub-area 2C, increasing from the early 1990s to a peak in the early 2000s.

- A standardised CPUE index for swordfish caught by New Zealand vessels operating in region 2 was generated for the period 1993 to 2011. The GAM model and covariates used to standardise the data are summarised in OFP (2013). In contrast to catch rate trends in other fisheries operating with the region, catch rates generally increased over time, particularly from the mid-2000s. The resulting CPUE indices are presented in Figure 5.
- An alternative CPUE time series was developed for the Japanese charter fleet fishing off the west coast of the South Island of New Zealand. See SC9-SA-IP-08.

Spanish fishery (Fisheries 5 and 12): Operational longline data were provided by the Spanish for the years 2004-2011. Significant catches were taken in region 2, peaking in the late 2000s.

- Spanish fishery CPUE in region 2: A CPUE index was developed for swordfish caught by Spanish vessels operating in region 2 from 2004 to 2011. Notable problems in using these data for deriving a standardized CPUE index include the lack of operational factors available for standardizing effort (numbers of hooks was not included), and catch was expressed in units of weight (rather than numbers of fish). The CPUE index was standardised relative to latitude and longitude, as the main factor influencing proportions of swordfish within catches (OFP 2012). The resulting CPUE indices are presented in Figure 5. Catch rates generally declined across the time series.

Other longline fisheries (Fisheries 6, 13 and 14, region 1 and sub-areas 2N and 2C, 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. These fisheries included fleets from PICTs (e.g. Fiji, New Caledonia, Papua New Guinea, Tonga, Vanuatu, Cook Islands, French Polynesia, and Western Samoa), plus fleets from distant water fishing nations other than the key fleets discussed above. All data for these other fisheries were supplied as logsheet data and/or aggregated spatial data, with effort and catches raised as appropriate.

Key CPUE time series for region 1 were the DW_1C and Australian fisheries (Figure 5). The long DW_1C quarterly time series increased during the period 1975 to 2000, subsequently declined to the mid-2000s, and recovered slightly in recent years. The more recent shorter CPUE time series for Australia showed comparable patterns, declining to the mid-2000s and then recovering.

For region 2, three candidate CPUE time series were identified: the distant water longline fishery operating in region 2C (DW_2C), the New Zealand fishery in region 2 (NZ_2) and the Spanish fishery in region 2 (SP_2; Figure 5). The distant water time series showed a general increasing trend to the late 1990s, subsequently declined, before stabilising in the late 2000s. The Spanish time series showed a general decline across the more recent time period. In contrast to both these time series, the New Zealand time series showed a contrary pattern, with a general increase in catch rates from the mid-1990s, particularly following 2005. Both the Chinese Taipei and Spanish data used for the CPUE standardization, covered a wide spatial distribution of region 2, whereas the NZ_2 data were restricted to the exclusive economic zone of that country (OFP, 2013).

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. Considerable size data exist for this assessment (Williams et al. 2011), in particular very high coverage of the length frequency of the Spanish catch and weight frequency for the Australian and New Zealand catches (Table 2). For most fisheries, temporal coverage of the size frequency data was relatively limited (Figure 7).

Length data were provided based on two different length measurement methods: eye orbit–fork length (EFL), and lower jaw–fork length (LJFL). 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 LJFL from EFL using the following relationship:

$$LJFL = 1.0753 * (EFL + 6.898)$$

(Campbell 2008), and weight measurements were standardised to the equivalent whole (unprocessed) weight. 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.

Australian fisheries (fishery 4 in region 1): A large amount of weight data were available from the Australian longline fisheries from AFMA for the period 1997–2011 (Table 2, Figure 7). The weight data was originally sourced from the main fish processors receiving swordfish 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 collected by Australian observers on longline vessels operating in Australian waters. The relationship between the two measures was:

Whole weight (kg) = 1.3717 x (gilled-gutted weight (kg) - 0.5).

The relatively limited length frequency data from this fishery exhibited a mode at relatively low sizes (~100cm, Figure 3), comparable to that sampled from SP_1 and DW_1N from region 1. This corresponded with a mode at relatively low weights seen in the substantial number of weight frequency samples from this fishery (Table 2). The median weight in the time series of data from this fishery also available from 1997 showed a general decline over the period 1997-2011 (Figure 8).

New Zealand fishery (fishery 11, region 2): Length data were available from observers on board New Zealand longline vessels during 1992–2011. Data were supplied by MFish with lengths measured as LJFL.

Length frequency data from this fishery showed a mode at relatively small sizes, but the size range sampled was wide (Figure 3). Substantial weight frequency samples were available from 2004, showing a mode at relatively low weights, comparable to that seen in AU_1 (fishery 4). Median weight in the samples from this fishery declined notably across the short time period 2004-2011 (Figure 8).

Distant water fishing nation fisheries (fisheries 1, 2, 3, 7, 8, 9 and 10, regions 1 and 2): Within region 1, the following data were available:

- in sub-area 1N (fishery 1), length frequency data were available from this fishery between 1992 and 2011, while weight frequency data were available across the period 1997 to 2002, with data being unavailable in a number of years (Figure 7). Similar to the Australian (AU_1, fishery 4) and Spanish (SP_1, fishery 5) fisheries, the length frequency from DW_1N had a mode at relatively low sizes. The limited weight frequency data available exhibited a mode at relatively higher weights.
- Within sub-area 1C (fishery 2), length frequency data were primarily available between 1991 and 1998 with sporadic samples after that time. Examining the combined length frequency distribution from this fishery, the mode in the data was at larger sizes than in the majority of other fisheries.
- Within sub-area 1S (fishery 3), length frequency data were sporadically available from 1991 to 2001.

Examining the length frequency distribution from these fisheries, the mode in the data increased in size from north to south in region 1, with the limited samples available from the distant water fishing fleet operating in sub-area 1S catches in particular containing samples with a high proportion of relatively large individuals. The very limited weight frequency samples from fishery DW_1N showed a mode at relatively larger weights (in comparison to the AU_1 and Other_1 fisheries where a greater number of samples were available).

Within region 2, the following data were available from the distant water fleets:

- From fishery 7 (DW_2N), samples were available between 1990 and 2011, with increasing temporal frequency and quarterly sample sizes toward the end of the time series. Limited weight frequency samples were sporadically available over the period between 1996 to 2010.
- From fisheries 8 and 9 (DW_2C divided pre- and post-2001), length frequency samples were available from 1987 to 2011. These were primarily concentrated in the early and later years of this period. No weight frequency data were available from this fishery.
- From fishery 10 (DW_2S), limited length frequency samples were available from quarters during the period 1988 to 2006.

Length frequency samples from the distant water longline fisheries in region 2 showed comparable distributions in 2N and 2C, with some increase in size moving south. However, the limited samples from the fishery to the south (DW_2S, fishery 10) were of notably larger lengths than seen in all other fisheries in this sub-area. Weight frequency samples from the northern fisheries were comparable to those from the 'Other' fisheries in that sub-area. In DW_2N, the median weight within the samples showed a general increase through time over the period 1996-2010 (Figure 8).

Spanish fishery (fisheries 5 and 12, regions 1 and 2): length frequency samples were available from the Spanish fleet operating in region 1 during two quarters of the year 2004. A much greater data set was available from fishery 12 in region 2 over the period 2004 to 2010. The limited length samples from the Spanish fishery in region 1 (SP_1, fishery 5) showed a mode at relatively low sizes (~100cm), comparable to the Australian fishery (AU_1, fishery 4), and another at larger sizes (150-200cm). A greater number of length samples were available from fishery 12 (SP_2) contained a mode around 150-200cm.

Other fisheries (fisheries 6, 13 and 14, region 1 and sub-areas 2N and 2C): Length data were available from fishery 6 from 1993, with consistent quarterly samples collected during the period 1998–2011; data from fishery 13 were available from 1992, with consistent quarterly sampling from the period 1994–2011; data from fishery 14 were available from 1993, with consistent quarterly sampling from the late 1990s. Notable weight frequency data were also available from fisheries 13 and 14, from 1993 to 2011 and 1994 to 2011 respectively.

Length frequency data from the other longline fisheries in regions 1 (Other_1, fishery 6) and 2 (Other_2N and Other_2C, fisheries 13 and 14) contained modes around 150cm. Examining the weight frequency data, these other longline fleets operating in regions 1 and 2 had modes at larger weights than seen in the Australian and New Zealand fisheries. For these fisheries, the median weight in the samples fluctuated over time. Those from Other_1 and Other_2N both showed a general increase in mean weight since 2005, while those from Other_2C showed a general decline from a peak in 1995 (Figure 8).

Size data were aggregated by fishery and time strata (year/quarter). Length data were aggregated into 31 10-cm size classes (2–312 cm EFL), which is the same coarse stratification used for the 2008 assessment. Weight data were aggregated into 31 10-kg intervals (2–312 kg whole weight).

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

As with any model, various structural assumptions have been made in the southwest swordfish 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 swordfish model are discussed below and summarized in Table 5.

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 growth and length-weight relationships, and there is evidence of spatial heterogeneity in both sex ratios and size composition (Davies et al. 2005).

There are observed differences in the size (length and/or weight) structure of the catch among fishery sub-areas of the model region (see Figure 2). These spatial differences were addressed through the method and sub-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 swordfish 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 fisheries (Figure 7). As described in Section 4.6 (Catchability), there were six standardized effort series from longline fisheries available for the model fitting procedure (DW_1C, AU_1, DW_2C (pre- and post-2001), SP_2, NZ_2). The most significant and sustained component of the catch from the model region and throughout the time period is from the Distant Water longline fisheries in regions 1 and 2 (DW_1C, and DW_2C pre- and post-2001). 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. Whereas tagging data informed the assumptions for movement, no tagging data were included in the fitting 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 0.025 times the actual sample size for the AU and NZ 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- and weight-frequency data from 'Other' fisheries (see Section 3.5) 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). Swordfish spawn in the tropical and sub-tropical latitudes (Young & Drake 2002) following seasonal migrations. As for the 2008 assessment, recruitment to the model population was assumed to be annual and occurs in the first quarter.

The distribution of recruitment among the two model regions was estimated within the model and allowed to vary over time in a relatively unconstrained fashion. The time-series variation in total annual recruitment was somewhat constrained by a penalty having a variance equivalent to a CV of about 0.2 (normal scale). This is a moderate 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 long-term 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 weak penalty was applied to deviation from the SRR so that it would have negligible effect on the annual 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. In contrast with the 2008 assessment, where the steepness of the stock recruitment relationship was performed with two alternative fixed values of steepness (0.65 and 0.9), in the current assessment 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).

4.3. Growth, maturity and natural mortality 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, some parameters can be fixed through time. For this assessment, specifically the growth rate, maturity ogive and natural mortality schedule values were fixed at the values assumed in the 2008 assessment because no new published estimates were available.

The two swordfish growth estimates described in the 2008 assessment provided alternative scenarios (Figure 9). These were:

- CSIRO-developed estimates from Australian age samples (Young et al. 2008);
- NMFS-developed estimates from Hawai'i age samples (DeMartini et al. 2007).

In each case, the mean of the male and female curve was used as fixed input, with variance on length-at-age inflated to cover both sexes. Ignoring the sexual dimorphism that is known to occur in swordfish (and undoubtedly relates to other important life history characteristics like M) is a potential source of bias. However, given the overall uncertainty in growth rates at present, sex dimorphism is probably not the highest priority issue to resolve. These two growth curve assumptions were only considered in conjunction with specific maturity and mortality vectors (Table 4, see below) and within this report will be termed the Hawai'ian and Australian 'schedules'. While the mean lengths-at-age were fixed at the published values, the variances were estimated when fitting the population model.

In the absence of new information, the two swordfish maturity schedules described in the 2008 assessment were used in the current assessment to provide alternative scenarios (Figure 9). These were:

- the age of 50% maturity = 10 years (Young and Drake 2002);
- the age of 50% maturity = 4 years, one of the more extreme maturity interpretations used in other swordfish assessments.

Given the poorly validated methods of age estimation, it follows that natural mortality estimates are also highly uncertain. There are a broad range of M values assumed in other swordfish assessments worldwide, ranging from at least 0.2 – 0.5. As in the 2008 assessment, eight different assumptions were developed, four corresponding to each of the two growth curve options described above, representing high and low mortality-at-age trajectories, with and without spawner effects (i.e. mortality increased once the age-at-maturity was reached; see Kolody et al. 2008) and defined in Table 4.

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

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.

4.4. Length and Weight

The parameters for the relationship between LJFL and whole weight were obtained from Davies et al. (2005) based upon observer samples for both sexes combined, $n = 2835$.

4.5. Movement

An estimate of swordfish migration rates between the two regions of the current model was developed by Evans et al. (2012). They estimated diffusive mixing across the boundary at 165°E (diffusion rate, $D = 0.11$) as the best estimate of movement between regions at this time.

Evans et al. also strongly recommend examining the sensitivity of this assumption, including alternative interpretations at the extremes (i.e. very high and zero mixing), in recognition that this estimate is highly uncertain (and qualitatively wrong if spawning populations really are isolated). Three other values of diffusion were examined in the sensitivity analyses (zero movement, and approximately half, and twice, the recommended value). Diffusion rates were translated into quarterly bulk transfer coefficients calculated for model input values based upon a "key" developed by Kolody and Davies (2008, SC4-SA-IP2, *see* Figure 16), that assumes instantaneous and complete mixing of the population within regions.

4.6. 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 (i.e. longlines) in different fishery sub-areas of the model region may be proxies for spatial structuring of the swordfish population by size. The selectivities at age for the longline fisheries were estimated using two forms of parameterisation: cubic splines and asymptotic forms (
Table 5). Each selectivity spline function was parameterised with four nodes allowing considerable flexibility in the functional form while minimizing the number of parameters required to be estimated. The asymptotic selectivities were assumed to be non-decreasing with the first age class for common terminal selectivity being 9+ years.

4.7. Catchability

Catchability was assumed to be constant over time for those fisheries where 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 represent the best available indices of relative abundance for the stock.

Catchability for all other fisheries that lack 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.

4.8. 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 relationship. For all fisheries, a penalty weight scaled by the square root of the effort was applied to the effort deviations, to reflect the amount of effort and its uncertainty. For the fisheries to which the model was fitted to standardized effort, the time-variant precision estimates (Figure 6) were applied multiplicatively to the penalties, i.e. as temporal effort deviate penalties that are higher for more precise effort indices.

4.9. 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.

4.10. 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.

4.11. 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.

4.11.1 Fishery impact

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

We approach this problem by computing biomass time series (at the region level) using the estimated model parameters including the annual estimated recruitments (excluding a spawner stock – recruitment effect), 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.

4.11.2 Yield analysis

The yield analysis consists of computing equilibrium catch (or yield) and biomass, conditional on a specified basal level of age-specific fishing mortality (F_a) for the entire model domain, a series of fishing mortality multipliers (*fmult*), 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. Exploratory analyses

The 2013 stock assessment of swordfish in the south-western Pacific Ocean significantly builds upon the work of Kolody et al. (2008) with new assumptions on stock structure and geographic model regions, as well as new and updated data sets. As a result of these fundamental differences in model structure, no stepwise development of the model from that of the previous assessment was possible. Instead, the full range of the Pre-Assessment Workshop's recommended key model runs (OFP 2013) were undertaken at each stage of the model development. In these runs alternative CPUE time series were input, including the alternative New Zealand CPUE index for the Japanese charter fleet, and this implausible run was rejected.

For these exploratory model runs, likelihood profiles in respect of the mean recruitment parameter were examined. Contrast in the profile assisted in identifying whether sufficient information was available for estimating absolute abundance given the assumptions used in the development. This diagnostic was most useful for selecting the assumed formulations of the selectivity assumptions, and in achieving plausible solutions for the full range of key model runs requested. Finally, the model selected from the range of key model runs for the Reference case, was that which obtained the best possible fit to the observations.

5.2. Sensitivity analyses

Analyses were undertaken to test a reference case model (**Ref.case**) sensitivity to: assumptions for the standardized CPUE time series to which the model was fitted; the eight options for growth rate/maturity/natural mortality; stock-recruitment relationship steepness; movement; and, the relative weight of the size-frequency data in the model fit. These were specified according to the Pre-Assessment Workshop's recommendations (Table 6) and the model run names and descriptions are listed in Table 7.

5.2.1 Movement

In addition to providing a recommended diffusion rate of 0.11 for the Ref.case model, Evans et al. (2012) also recommended exploring model sensitivity to this rate due to the uncertainty in the estimate. Rates equal to 0.0, 0.05 and 0.25 were considered and the region-specific quarterly block transfer coefficients were obtained using the method described in Section 4.5 using a block sizes of 25° and 65° for regions 1 and 2, respectively.

5.2.2 CPUE indices

Due to the close consistency in the trends of the DW_1C and AU_1 indices, the Pre-Assessment Workshop recommended that the model be fit to these indices for region 1 in the Ref.case model (OFP 2013) and all sensitivities (Table 6). Reasonable consistency was evident in the trends of the DW_2C post-2001 and EU_2 indices, and the Ref.case model was fit to these indices in region 2. For this region, model sensitivity was explored for: excluding the EU_2; and, replacing the EU_2 index with NZ_2 index.

5.2.3 Growth/Maturity/Mortality

The eight options for the mortality-at-age schedules were explored (section 4.3), and for each the associated maturity-at-age and growth schedule (Hawai'ian or Australian) were assumed. The GAMHS option was assumed for the Ref.case.

5.2.4 Steepness

A fixed value of 0.8 was assumed for the Ref.case, and fixed values of 0.65 and 0.95 were tested.

5.2.5 Relative weight of size data

Moderate relative weight was assumed for length- and weight-frequency data for the Ref.case. The relative influence of these data was reduced by reducing the effective sample size to 0.0125 and 0.005 times (respectively) the individual samples, for the AU/NZ and Other fisheries, respectively, with a maximum sample size of 100.

The Ref.case and the fifteen sensitivity runs 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 each of the key model runs. These interactions were tested in a grid of 576 combinations of the various options for each of the five sensitivity factors, i.e. 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. The percent of grid runs in having these criteria was 2.6% (15 models). The remaining 561 models were all assumed to have uniform probability of being plausible, i.e. no relative weight was predefined for the factors examined, or the options within each. Using the plausible grid runs, 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. Reference case model selection from the sensitivities

In selecting a reference case model the approach followed was to aim for an ideal that demonstrates the best possible fit to the observations.

To move towards this ideal, it was necessary to remove sources of conflict among the CPUE indices because it was clear there are differences in trends between the CPUE indices from DW_2C and SP_2 compared to NZ_2 (Figure 5). 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 down-weighted” (Francis 2011). Accordingly, the available indices were considered in respect of how representative they were of the population. Factors suggesting the DW_2C fishery provided a representative index of relative abundance of the population included:

- providing a long time series of information (Hoyle et al. 2013) that was likely to have reasonably consistent operational factors throughout the time period; and,

- provided information over the a wider geographic range in region 2 compared to other fisheries with an estimated selectivity over a wide range of recruited age-classes.

Accordingly, the NZ_2 indices were excluded from the Ref.case model.

Following the recommendations of the pre-assessment workshop (OFP 2013) other settings for the Ref.case model were maintained. A key area of uncertainty arose from the assumptions of growth patterns used within the model. To identify the model run that best achieved the ideal, model diagnostics and resulting change in the total objective function were noted when comparing the use of alternative growth assumptions. The use of the Hawai'ian schedule, combined with the associated high mortality and spawner effects in natural mortality, resulted in a substantially better fit to the data, i.e. the best objective function value. Consequently, the GHMHS option was chosen for the Ref.case model.

The likelihood profile for the Ref.case model fit with respect to the parameter "mean Recruitment" is shown in Figure 10. There was a clear global minimum in the objective function.

6.2. 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 11). The log total catch residuals by fishery are shown in Figure 14. The residuals are all relatively small and, for the key fisheries (DW_1C, AU_1, DW_2N, DW_2C pre- and post-2001, NZ_2 and SP_2) generally show even distributions about zero. For some fisheries, a spread in the catch residuals was visible, suggesting some lack of fit to the catch data for these fisheries; however, these occurred mostly for fisheries to which the CPUE was fitted, and there were no consistent temporal trends (Figure 12).

- 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 13). 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 fisheries, and in particular the DW_1C and SP_2 fisheries providing the standardized effort, the effort deviations (over the standardization period) are relatively small and there is no evidence of a strong temporal trend. This indicates that the catch and effort data from these fisheries are consistent with the estimated trends in the vulnerable biomass for the fishery.

- A generally good fit to the observed CPUE was obtained for the key fisheries time series used in the model fit (Figure 14). Model predictions are consistent with the general increasing and declining trends in the DW_1C time series, as well as much of the inter-quarterly variability. Similarly, the declining and subsequent increasing trend in AU_1 is captured. For region 2, the generally flat trend in the DW_2C_pre-2001 series is well described by the model. The extreme values in the DW_2C and SP_2 series are not predicted by the model, however these observations have high observation error (Figure 6). For the DW_2C_post-2001 and SP_2 series, the general declining and then increasing trends are well described by the model.

- Overall, there is generally a good fit to the observed weight frequency data for the fisheries for which high relative weight was assigned to these data (AU_1, NZ) with good correspondence between observed and predicted median weights (Figure 15). In both cases, the median weight showed a decline in the more recent period. It was noted there is slight positive bias in the NZ_2 fit. Residual patterns were seen in the fits to both data sets (Figure 18) with positive residuals for the smaller and moderately large fish (under-estimated) and negative residuals in the middle of the size range (overestimated). While a poorer quality fit was obtained to the data for the Other_1, DW_2N, Other_2N, and Other_2C fisheries, the general trends in median weight were described by the model. The model fit to the more recent samples from fisheries Other_1 and Other_2N was negatively biased, although the median weight observed was generally within the confidence intervals. In these cases, a notable increase in observed median weight within the recent period conflicts with the general downward trend in other fisheries and the model prediction. Residual patterns in the fit to the weight data for these fisheries showed some large residuals, with Other_1 and Other_2N showing some overestimation at small sizes in the recent period in particular (Figure 18).

- The AU_1 and NZ_2 fisheries were assigned high relative weight to the length data in the model fit, and a good fit was obtained for the NZ fishery over most of the time series, however, the fit to the Australian data was relatively poor, with the model consistently over-estimating the median sizes caught (Figure 16). Fisheries for which low relative weight was assign to the length data, exhibited relatively good fits to these data (DW_2N, DW_2C_pre01, SP_2, Other_2C), but also poor fits (DW_1N, DW_1C, DW_1S, Other_1, DW_2S, and Other_2N), with the model under-estimating median lengths in the DW_2C_post01 fishery (Figure 16). The poor fits most likely reflect to some extent the sample sizes being relatively low, for example the earlier period of DW_2N data set (Figure 7). Strong patterns were seen in the residuals for the fit to the length frequency data from the AU_1 fishery, with model predictions being consistently negatively biased for smaller fish and positively biased for large fish. As there are more numerous weight-frequency data from this fishery, this suggests some inconsistency between the two data sets. No consistent patterns were visible for fisheries for which reasonably good fits were obtained (e.g. NZ_2 and Other_2C). Negative residuals are evident for the DW_1N fishery, where the model could not generally fit the relatively small fish, particularly early in the time series when sample sizes were relatively limited. Positive residuals were evident in the fit to the DW_2S fishery data where the model fit was generally negatively biased and unable to reconcile the larger individuals within this relatively small number of samples. There are some temporal trends seen in the residuals of the fit to the length frequency data, e.g. more positive residuals for large fish in the early part of the DW_2C_post2001 time series, and more positive residuals for small fish in the early part of the Other_2N time series (Figure 17). In these cases, the sample sizes in these periods were relatively small (Figure 7).

6.3. Model parameter estimates

6.3.1 Catchability

The annual catchability (although allowed to vary seasonally) was held constant for the fisheries having standardized CPUE indices to which the model was fitted (DW_1C, AU_1, DW_2C_pre-2001, DW_2C_post-2001, SP_2 (Figure 19). Catchability was allowed to vary temporally for all other fisheries and comparisons of the estimated trends reflect the conflict among the CPUE indices, e.g. the NZ_2 series shows a consistent increasing trend which reflects the increasing CPUE, while that of the DW_2C_post-2001 and SP_2 fisheries are generally declining. A steady upward trend in catchability for the DW_2N fishery is visible and this might indicate changes in the fleet composition in recent years.

Strong seasonal trends in catchability are evident from most fisheries, but most pronounced in the central and southern sub-areas. For example, catchability of the AU_1 fishery was highest during the first quarter and lowest in the third quarter, while the NZ_2 and DW_2S fisheries were highest in the third and fourth quarters. The magnitude of the seasonal variability in catchability increased with increasing (southern) latitude.

6.3.2 Selectivity

An immediate feature of the estimated selectivity functions is the young age at which fish become vulnerable to the fisheries, a result of the fast growth rate implied by the Hawai'ian schedule. Swordfish become vulnerable to the main fisheries in regions 1 and 2 (e.g. AU_1, DW_1C, DW_2C, SP_2 and NZ_2) from 1or 2 years of age, and are fully recruited by age 3-4 in many fisheries (Figure 20). Where a spline function was assumed for fisheries (e.g. DW_1N, NZ_2, Other_2N, Other_2C), however, full selectivity may be achieved only at ages over 10 years. These fisheries display bi-modal selectivity functions with a large mode for fish of high ages. In contrast, an unusual spiked spline function was estimated for the DW_1C fishery. Despite a poor fit to the size data from fishery DW_2S, the selectivity estimates for this fishery were constant over all ages. This may reflect conflict between the size data from this fishery and other data fitted in the model.

6.3.3 Growth

The fixed Hawai'ian growth schedule assumed for the Ref.case is shown in Figure 21. Growth rates are high during the first 4 years at which age fish achieve a mean LJFL of nearly 160 cm. The estimated variability in mean length-at-age was relatively high with considerable overlap in the distributions for the fully recruited age classes, 4 years and older. However, the rapid increase in mean length-at-age between 2 and 5 years means there is little overlap in the distributions for the recruiting age classes.

6.4. Stock assessment results

This section principally documents the results of the Ref.case model run, but makes reference to the sensitivity runs (Table 7). 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 8 and the key results are provided in Table 9.

6.4.1 Recruitment

The temporal variation in mean recruitment over the model period is moderate (Figure 22). While there is a general decline in average recruitment over the period 1952-2011, occasional large recruitment events were estimated, particularly in the period between 1975 and 1995. There was no clear periodicity in these large recruitment events. Recruitment estimates have broad confidence intervals indicating substantial uncertainty, with a slight reduction in uncertainty following the mid-1990s, when more size data become available. No consistent decline is evident in the recent period (since the mid 1990s).

6.4.2 Biomass

The annual trends in total and adult biomass are consistent with the temporal trend in recruitment described in the previous section (Figure 23). Biomass was estimated to have declined slightly from a high during the 1950s through to the late 1970s, then increased during the period of the high recruitment events in the late 1970s to mid-1990s. However, despite relatively consistent annual recruitments, the biomass subsequently declined to lows in the late 2000s, with a slight increase in recent years. Biomass has remained above the level which supports the *MSY*. There is a high level of uncertainty associated with the annual biomass estimates, which decreases slightly from the late 1990s. This reduced uncertainty may be a result of more size data only being available since the 1990s for the key fisheries.

The sensitivity of model biomass estimates to the assumptions tested in the other key model runs are presented in Figure 24 (a&b). Absolute biomass was sensitive to alternative assumptions on mortality when the Hawai'ian schedule was assumed, but not the overall trend (Figure 24a, top). Assumption of a mortality schedule without a spawner effect produced a higher total biomass estimates (around 20% higher, implying a more productive population). Assuming a low mortality schedule (GHML) had little effect on the biomass estimates, while incorporating the spawner effect led to a decrease in estimated total biomass under this mortality assumption.

Assumption of the Australian schedule (Figure 24a, bottom) led to a smoother total biomass trajectory, most likely a result of the lower assumed mortality associated with this growth option, and no increase in biomass is estimated in the most recent years. The equivalent run to the Ref.case is GAMHS, which resulted in higher total biomass estimates, and a slightly steeper decline in total biomass in the recent period. Unlike the runs where the Hawai'ian schedule was used, the incorporation of the spawner effect led to higher, rather than lower, biomass estimates, and greater differences in the biomass trajectories particularly in the recent period.

Of the other key sensitivity run settings, lower and higher values for stock-recruitment steepness (**steep_0.65**, **steep_0.95**) have negligible impact on absolute biomass estimates (Figure 24b, top), but substantially change equilibrium biomass estimates. Assuming low and much higher movement parameters had a negative (around a 25% reduction) and positive (around a 20% increase) effect on biomass, with a slightly steeper decline in biomass in the recent period seen at higher movement rates (**mvmnt_0.25**), and a shallower decline at lower movement rates (**mvmnt_0.05** and **movmnt_0**).

Removal of the SP_2 CPUE time series from the fit (**cpopt_CP2_TW**) had a small negative effect on estimated biomass, but no effect on the trend (Figure 24b, bottom). However, inclusion of the increasing New Zealand CPUE trend in place of the SP_2 series (**cpopt_CP2_TW_NZ**) led to notably higher biomass levels (almost twice that of the Ref.case), and no clear declines in biomass.

Down-weighting the size data within the model fit procedure (**sz_wt_80_200**) led to a small increase in estimated biomass (Figure 24).

6.4.3 Fishing mortality

Fishing mortality (exploitation) rates for both juvenile and adult swordfish are estimated to have increased sharply in the mid 1990s (Figure 25a) following the significant increases in catches at that time (see Figure 1). Since that time, fishing mortality rates for both juvenile and adult swordfish steadily increased until the early 2000s, when juvenile fishing mortality stabilised around 0.09. In contrast, adult fishing mortality continued to increase up to a peak in the late 2000s around 0.13, declining to 0.09 in the most recent years.

The comparability between fishing mortality rates of juvenile and adult swordfish relates to the early age at which individuals are recruited to the fishery under the Hawai'ian schedule. Using the alternative assumption of the slower Australian schedule results in comparable patterns in mortality (Figure 25b). The selectivity of the fishing gears under this assumption shifts the age of recruitment to the fishery to later ages (equating to comparable sizes of capture), but also corresponds to a shift in the age at maturity to age 10 years. Resulting fishing impacts are therefore comparable (Table 9). This assumption does have a significant impact on stock productivity, however (see below).

6.4.4 Fishery impact

An indicator of the impact of fishing on the stock is to compare the biomass trajectories with fishing and the predicted biomass trajectory in the absence of fishing. The impact can be expressed as a proportional reduction in biomass ($1 - B_t / B_{0t}$). While 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, within this assessment all fisheries are of the same group (longline). Hence fishery-specific impact plots are not presented.

The reference case model indicates that the entire fishery has had a substantial impact on the levels of total and spawning biomass, with current levels being 32% and 45% lower than they would have been in the absence of fishing (Figure 26, Table 9). Under the slower Australian schedule (GAMHS), the total and spawning biomass were 45% and 59% lower.

6.4.5 Yield analysis

The yield analyses conducted in this assessment incorporate the SRR (Figure 27) into the equilibrium biomass and yield computations. The Ref.case model steepness coefficient of the SRR was assumed to be 0.8.

Equilibrium yield and total biomass as functions of multiples of the 2010–2011 average fishing mortality-at-age (Fmult) are shown in Figure 28. Yield is maximized at Fmult = 1.98 for an *MSY* of

10,420 t per annum, slightly higher than the average annual catch from the model region in the recent period (Figure 1). This implies that the ratio $F_{current}/\widetilde{F}_{MSY}$ is 0.51. The equilibrium total biomass at MSY is estimated at 60,290 t, approximately 40% of the equilibrium unexploited biomass (Table 9).

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 fall slightly to 54% and 103% above the levels that support MSY, respectively.

There is a high level of uncertainty regarding the growth rate of swordfish. The sensitivity of the model to the assumed growth trajectory (Hawai'ian vs Australian schedules) was investigated. The Ref.case model equilibrium yield, fishing mortality and biomass estimates were most sensitive to this source of uncertainty (Figure 29), with the $F_{current}/\widetilde{F}_{MSY}$ ratio having a range from 0.40 to 1.77, and $SB_{current}/SB_{MSY}$ from 1.15 to 2.54 (Table 9). While as noted, the absolute estimates of fishing mortality were comparable between growth assumptions, the equilibrium fishing mortality, and hence, productivity of the swordfish stock, and therefore its ability to withstand current levels of exploitation, are quite different. Under the Australian schedule, Fmult estimates are < 1, while under the Hawai'ian schedule the estimates are > 1.4 (Figure 30). Similarly, estimated current stock status relative to SB_{MSY} under the Australian schedule was more pessimistic (1.2 to 1.4).

Of the other key sensitivity run settings, the relative equilibrium biomass levels that support MSY were not sensitive to excluding the SP_2 CPUE index from the model fit (**cpopt_CP2_TW**), (Figure 29), e.g. SB_{MSY}/SB_0 was 0.24 and 0.24 for the Ref.case and cpopt_CP2_TW runs, respectively. However, the model is highly sensitive to the inclusion of the New Zealand CPUE data; the **cpopt_CP2_TW_NZ** run. MSY increased by 88%, and $F_{current}/\widetilde{F}_{MSY}$ decreased to 0.19 in this run (Table 9), and the yield curve was notably 'flat topped' (Figure 29), and did not reach an inflexion point within the range of F-multipliers examined (Figure 30).

Lower and higher values for stock-recruitment steepness (**steep_0.65**, **steep_0.95**) substantially change equilibrium biomass estimates (Figure 29). Higher steepness led to higher yields and lower SB_{MSY}, and vice versa, resulting in more pessimistic and optimistic predictions of MSY-based estimates of stock status, respectively (Table 9).

Examining alternative movement rates between the two model regions (**mvmnt_0**, **mvmnt_0.05**, **mvmnt_0.25**) compared to the Ref.case (where the movement rate was set at 0.11) did not strongly affect relative equilibrium biomass levels that support MSY; for example SB_{MSY}/SB_0 was 0.24 across all runs. However, estimates of yield and stock status relative to equilibrium biomass were sensitive, particularly where no movement was assumed. In this case, $F_{current}/\widetilde{F}_{MSY}$ increased to 0.65 from 0.50 (Table 9). The impacts on stock status were not consistent, although assuming no movement implied more pessimistic stock status, and higher movement rates more optimistic stock status levels, however, low movement rates implied even more optimistic stock status.

Further down-weighting of the size frequency data (**sz_wt_80_200**) had a relatively small impact on the estimated parameters (Table 9).

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. Temporal trends for total and spawning biomass in relation to these reference points are provided in Figure 31 for the reference case. The trends of the two are similar, with the spawning biomass values being slightly higher on the relative biomass axis. Fishing mortality rates were initially relatively low up to the late 1990s, after which they steadily increased to levels around $0.5F_{MSY}$. After a slow decline to 2000, total and spawning biomass have declined steadily. The Ref.case estimates have remained above the B_{MSY}, and SB_{MSY} levels, being around 58% and 117% higher than those levels in the recent period. The decrease in the estimated fishing mortality in the final year of the assessment (2011) is noted, although this value is amongst the most uncertain over the time period.

The spawning biomass-based Kobe plots for the Ref.case and for the key model runs (one-off sensitivity runs) are compared in Figure 32 and Figure 33. Although the general temporal patterns of the two reference points (SB/SB_{MSY} and F/F_{MSY}) are similar in respect of increasing fishing mortality and decreasing spawning biomass, the current estimates relative to the F_{MSY} and SB_{MSY} levels differ among the runs reflecting the sensitivity of the model equilibrium yield and biomass estimates to the assumptions tested. Overall, the largest uncertainty arose through the assumption of growth within the model settings. Moving from the Hawai'ian schedule to the slower Australian schedule led to notably more pessimistic results, with lower recent spawning biomass levels and estimates of fishing mortality greater than F_{MSY} (making up 25% of the 16 key model runs performed). Where this slower growth is combined with the lower mortality assumption (e.g. GAML and GAMLS), the spawning stock size in recent years is close to SB_{MSY}. While trends and stock status were insensitive to removing the Spanish standardised CPUE time series from the data (cpopt_CP2_TW), inclusion of the increasing New Zealand CPUE trend in its place (cpopt_CP2_TW_NZ) led to more optimistic results with lower impacts on spawning biomass and much lower fishing mortality levels. A more pessimistic estimate of current stock status was estimated for the run assuming a lower steepness (steep_0.65) and optimistic when higher steepness (steep_0.95) was assumed. Temporal trends and stock status were relatively insensitive to assumptions for movement, and the weighting applied to size data within the model fit.

The range for the estimates of current stock status (based upon the period 2008-11) relative to these reference points for the key model runs is presented in Figure 33, which illustrates a high level of uncertainty, largely due to the growth assumptions, high steepness and inclusion of the NZ_2 CPUE index.

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 Figure 34 and Figure 35, respectively, for the 561 plausible runs included in the summary. While there was not clear separation in SB_{curr}/SB_{MSY} between growth assumptions, there was clear separation when examining F_{curr}/F_{MSY} with as mentioned earlier, the estimate under the slower Australian schedule being notably higher. A similar but less significant pattern was seen under alternative steepness assumptions, with a lower steepness equating to higher F_{curr}/F_{MSY} and lower SB_{curr}/SB_{MSY}. Where no movement was assumed, more optimistic estimates of stock status were obtained. 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 (Figure 36), the range of grid estimates was extremely broad, with a median value for $SB_{current}/SB_{MSY}$ = 2.17 (5th and 95th percentile range = 1.14 – 4.72) (Table 8). The probability that $SB_{current}/SB_{MSY}$ is < 1 was 2.0%. The range largely reflects the large amount of uncertainty in these estimates attributable to the assumptions for growth, steepness, including the NZ_2 CPUE index, and assuming zero movement. The median estimate for $F_{current}/F_{MSY}$ was 0.70 (5th and 95th percentile range = 0.23 – 1.81) (Table 9). Assumptions for growth again, and assuming low steepness, largely contributed to this uncertainty. Across the uncertainty grid, where the Hawai'ian schedule was assumed, the proportion of grid runs where $F_{current}/F_{MSY} > 1$ was less than 2% (0.018). Where the slower Australian schedule was assumed, this proportion increased to 51% (0.507). The effects of each of the individual growth assumptions on the grid estimates of stock status are clearly visible in the separation of grid cell estimates into groups associated with each assumption (Figure 36).

6.4.6 Stock assessment conclusions

The main conclusions of the current assessment (with estimates of stock status based upon the plausible range of key model runs) are as follows.

1. The relatively steep decline in biomass over the period 1997 to 2011 over all key model runs, despite the no concurrent temporal change in recruitment, is a notable feature of the current assessment. It is

concurrent with large increases in catch particularly in region 2, and declines in CPUE and median fish sizes in the main fisheries. The recent increase in the AU_1 CPUE index is best described by the Ref.case model for which the faster Hawai'ian schedule is made; whereas no increase is predicted when the slower Australian schedule is assumed.

2. Estimates of absolute biomass and equilibrium yield were sensitive to including the NZ_2 standardized CPUE time series in the model fit. The SP_2 CPUE time series in region 2 was selected for fitting the Ref.case model because this time series was considered to be consistent with the trend of the DW_2 index and both data sets were derived from a wide spatial distribution. The large contrast among the available indices for region 2 creates conflict in the data to which the key model run **cpopt_TW_NZ** was fitted, evident in the large differences in model estimates relative to the Ref.case. It is to be determined which of the indices may be representative and indices "that are believed to be unrepresentative should be discarded; they certainly should not be retained and down-weighted" (Francis 2011). The recent declines in the Ref.case model indices for region 2 appear to be consistent with declines in median size over the same period, whereas the NZ_2 index is in conflict with this trend, and is derived from a limited spatial distribution. On this basis, the **cpopt_TW_NZ** model is considered unreliable, or at least highly uncertain, and this model estimate is **excluded from the ranges of the key model runs provided below**.
3. The key source of uncertainty in this assessment is the assumed growth/maturity/mortality at age schedule. Estimates of equilibrium yield, the associated reference points and therefore stock status are highly sensitive to this assumption. Whereas relatively optimistic stock status is predicted under the assumption using the Hawai'ian schedule, the Australian schedule led to notably more pessimistic results, with lower recent spawning biomass levels and estimates of fishing mortality greater than F_{MSY}. Estimates of stock status are therefore highly uncertain with respect to this assumption. Across the uncertainty grid, where the Hawai'ian schedule was assumed, the probability of $F_{current}/F_{MSY}$ being less than 1 was less than 2%, while where the slower Australian schedule was assumed, this increased to 51%.
4. Total and spawning biomass are estimated to have declined most notably since the late 1990s, with more gradual declines before that time. Current levels of total biomass $B_{current}/B_0$ = 44 – 68 % and spawning biomass $SB_{current}/SB_0$ = 27 - 55% (range of key model runs).
5. 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 current period, spawning potential is at 26 - 60% of the level predicted to exist in the absence of fishing (range of key model runs).
6. Recent catches are between 82% of the *MSY* level and 102% above the *MSY* level of between 5299 and 12,730 mt (range of key model runs). Within this range,
    - assuming the Hawai'ian schedule produces estimates between 82% of the *MSY* level and 24% above the *MSY* level, while,
    - assuming the Australian schedule produces estimates that are between 53 and 102% above the MSY level.

    Based on these results, we conclude that under the Hawai'ian schedule current catches are around the MSY level, while under the Australian schedule current levels of catch are above the MSY level.

7. Fishing mortality for adult and juvenile swordfish is estimated to have increased sharply in the mid 1990s following the significant increases in catches at that time. $F_{current}/F_{MSY}$ was estimated to be between 0.33 and 1.77 (range of key model runs). Within this range:
    - assuming the Hawai'ian schedule produces estimates between 0.40 to 0.70, while,
    - assuming the Australian schedule produces estimates that are between 1.06 to 1.77.

    Based on these results, we conclude that under the Hawai'ian schedule overfishing is not occurring, while under the Australian schedule overfishing is occurring.

8. The reference points that predict the status of the stock under equilibrium conditions at current F are $B_{F_{current}}/B_{MSY}$ and $SB_{F_{current}}/SB_{MSY}$, and range from 0.48 to 1.89, and 0.33 to 3.45, respectively (range of key model runs). Within this range:
   - assuming the Hawai'ian schedule produces estimates between 1.32 to 1.61, and 1.52 to 2.47, respectively, while,
   - assuming the Australian schedule produces estimates are between 0.48 to 0.95, and 0.33 to 0.91, respectively.

   Current stock status compared to these reference points indicates that the current total and spawning biomass are: $\frac{B_{current}}{B_{MSY}}$ from 1.15 to 1.85 and $\frac{SB_{current}}{SB_{MSY}}$ from 1.15 to 3.53, (range of key model runs). Within this range:
   - assuming the Hawai'ian schedule produces estimates between 1.51 to 1.58, and 1.86 to 2.54, respectively, while,
   - assuming the Australian schedule produces estimates are between 1.15 to 1.37, and 1.15 to 1.80, respectively.

   Under either growth/maturity/mortality schedule, current stock status is predicted to be above the level supporting *MSY*. **Based on these results, we conclude that the stock is not in an overfished state.**

9. **Based on these results above, and the recent trend in fishing mortality, we conclude that under the Hawai'ian schedule overfishing is not occurring, but under the Australian schedule, overfishing is occurring, the stock is not in an overfished state.**

7. Discussion

Comparison with 2008 assessment

This paper presents the 2013 assessment of swordfish in the south-western Pacific Ocean, updating the previous assessment done in 2008. 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 Chinese Taipei longline catch and effort data; standardised CPUE analyses of operational catch and effort data for Australian longline fishery; and New Zealand, and for the Spanish.

The main developments to model structural assumptions were to: assumed two model regions, biologically connected, based on the results of recent electronic tagging programmes, and relaxing assumptions such as the relative recruitment to each region; fixing steepness at 0.8; estimating spline and non-decreasing selectivities for the main longline fisheries. A new statistical assumption was to include time-variant precision in fitting the model to standardized CPUE indices. This assessment was aided by: the large increases in sampling and data collection in NZ and PICTs; the new standardised Chinese Taipei CPUE and its disaggregation in respect of targeting practice; and an index of relative abundance using Spanish catch and effort data.

Whereas the previous assessment was unable to derive reasonable estimates of biomass for the central south Pacific (model region 2), reasonable estimates were obtained for this assessment. The Ref.case model likelihood profile suggests sufficient information was available for estimating mean recruitment and therefore absolute abundance. This most likely is derived from the consistency in the declining trends in CPUE (DW_2C and SP_2) and the median sizes caught from region 2. In the case of region 1, the "two-way trip" illustrated in the DW_1C and AU_1 CPUE indices most likely provides sufficient "signal" about stock productivity, as was seen in the previous assessment (Kolody et al. 2008). The consistency among the data for key fisheries in region 2 may account for the increased certainty in this assessment compared to that of the 2008 assessment attempted over the same model domain.

The biomass trends of this assessment up to the mid 2000s were largely a function of fishing mortality rather than recruitment. Despite relatively consistent annual recruitments over this period, the biomass subsequently declined to lows in the late 2000s concurrent with the three-fold increase in catches, but followed by a slight increase in the last 2-3 years. Region-specific recruitments appear to be unique and are consistent with the CPUE and size observations in each region. In the case of region 1, recruitments in the most recent 5 years have increased which may reflect the fit to the CPUE increases in the DW_1C and AU_1 indices. Combined biomass has remained above the level which supports the MSY.

Sources of uncertainty

This assessment has included a reasonably thorough consideration of five factors (being both assumptions and inputs) in a series of sensitivity runs and a structural uncertainty analysis (grid). The results revealed notable uncertainty surrounding some of the key parameters included in the assessment model.

The overwhelming source of uncertainty in this assessment is attributable to the assumptions for the growth, maturity and mortality at age schedules. These were taken directly from the 2008 assessment in the absence of new information, and comprise two main schedules, being one derived from Hawai'ian and the other derived from Australian growth estimates. These two schedules lead to considerably different assessed stock status levels. As an indication of the relative impact of this assumption, whether the Hawai'ian or Australian schedule was assumed resulted in the probability of $F_{current}/F_{MSY} > 1$ being either 0% or 50%, respectively. While the effects of this uncertainty were substantial in respect of estimates of stock status, the absolute biomass and fishing mortality were less affected. This is because the model selectivity-at-age estimates shift to lower and higher ages depending upon the assumed growth and mortality schedules. This problem of growth uncertainty is magnified further by the fact that swordfish are sexually dimorphic and spatial heterogeneity in sex ratios have been reported (Davies et al., 2005, DeMartini et al. 2000). This has important implications for the model structure and biological processes. For example, the inability of the model to predict large individuals observed in the DW_2S fishery may illustrate misspecification of these processes, which might be addressed through the use of a sexual dimorphic growth curve where females grow larger.

The steadily increasing trend in the NZ_2 CPUE index contrasts starkly with the declining trends of the DW_2C and SP_2 indices. Whereas in the Ref.case model, that excluded the NZ_2 index, catchability parameters for this fishery were steadily increasing, including the index (in the cpopt_TW_NZ sensitivity model) entailed assuming constant catchability, which resulted in conflict with the DW_2C index. This raises the question as to which index is representative of changes in relative abundance. The NZ indices are derived data collected over a relatively small spatial range of region 2, and the increasing trend in the indices is in contrast to the declining trend in median fish size caught within the same fishery. Both the DW_2C and SP_2 indices are derived from data collected over most of the spatial range in region 2. It was therefore considered reasonable, and consistent with the view of Francis (2011), to remove this source of conflict in the observations for region 2, and not to regard the NZ_2 indices as representing trends in relative abundance. We recommend not including the cpopt_TW_NZ model among the plausible key model runs, and have not used it for reporting estimates of stock status.

A steadily increasing trend in catchability in the DW_2N fishery was estimated, particularly since the mid 1990s when catches increased notably. This contrasts with the DW_2C and SP_2 CPUE indices for the region 2 central sub-area, that show declines over the same period. The increases in sub-area 2N reflects the substantial increases in nominal catch rates and most likely reflects the changes in the fleet composition in recent years (Figure 4), and the consequent changes in targeting practices. Also, the possible effects of mixing with the eastern and northern Pacific ocean swordfish population are not well understood, and may influence temporal variation of catch rates in this part of region 2. However, the persistent nature of the trend identified over almost 20 years, makes this an unlikely explanation.

The model fit to the length frequency data from the DW_2S fishery revealed systematic negative residuals for small fish due to the negative bias in the model estimates of fish size; being due to the model's inability to predict the very large fish. We attribute this to reflecting the effects of the assumed growth curve which has a relatively low mean asymptotic length compared to the observations. The Ref.case model selectivity estimate for this fishery was "flat-topped" over all ages. When a gradually increasing and asymptotic selectivity was fixed for this fishery, a poorer fit was obtained overall (lower total objective function) despite achieving a somewhat improved fit to the DW_2S length frequency data. Even where a higher asymptotic mean length-at-age and lower natural mortality is assumed (key model run GAMLS), although producing a somewhat improved fit to these observations, this model still exhibits consistent patterns in the length residuals. This illustrates the conflict between these and other data in the model. It is proposed that this lack of fit is due to a model mis-specification of swordfish growth, as mentioned above, where the ages of large fish may be poorly estimated, and this will affect the model estimates of selectivity and total mortality.

The DW_1C CPUE time series includes unusual and consistent trends with sustained increases and decreases over time that seem unlikely in the case of a by-catch fishery operating during a period of relatively high estimated stock abundance. The trends directly affect the model recruitment estimates (Figure 22). A consistent pattern was evident in the length frequency residuals of this fishery, and a notable "spiked" selectivity was estimated. The relatively small length frequency sample available exhibits extreme observations in recent years, and may be inadequate for estimating the selectivity with reasonable certainty. The "spiked" selectivity might be a consequence of the relatively good fit to the long CPUE time series and may best describe the inter-annual variability in the index. This uncertainty may be addressed with improved historical size composition data for this fishery. An exploratory model run was performed where selectivity of the DW_1C and AU_1 fisheries were coupled (i.e. assuming selectivity in the non-target DW_1C fishery matched that in the targeted AU_1 fishery). A worse fit overall was obtained, particularly to the variability in the DW_1C CPUE. This was most likely due to the enforced wider selectivity spread over more age-classes within this fishery, leading to lower temporal variability in estimable catch rates. There was no significant change to estimated recruitment, suggesting the DW_1C CPUE series was still largely determining the temporal trend. There was also no substantial change to the model estimates of stock status overall, with lower values for equilibrium yield quantities due to the wider selectivity for this fishery that accounted for a long period of removals from the population.

Conflicts were evident in the model fit to the size composition data. Most obvious was the poor fit to the AU_1 length frequency data while a relatively good fit was obtained to the more numerous weight frequency data from the same fishery, illustrating a conflict in the median size of fish caught. This conflict most likely explains the consistent patterns in the residuals for this fishery, given the relatively large sample sizes available. Possible explanations for this conflict within the AU_1 size data include incompatible sampling protocol, or perhaps high-grading of swordfish prior to landing (because the weight frequency samples are sourced directly from commercial landings).

Conflict was also evident in the data for the DW_2C fishery. While a relatively good fit was obtained to the length-frequency data pre-2001, a relatively poor fit was obtained to these data post-2001. These data were assigned low relative weight in the model fit, and it is likely that the fit to the CPUE index was optimized in the model fit overall.

Estimates of stock status were highly uncertain due to the differences in the effect of the growth schedule assumptions. No conclusive evidence is currently available with which to select among these two assumptions, or with which to assign relative plausibility to each schedule. The combined effect of this uncertainty in growth when considered in combination with the other 4 model assumptions included in the uncertainty grid analysis is unknown. To re-evaluate the large uncertainty indicated in the assessment results, relative weights could 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. However, more information, particularly on the growth schedules is required for this approach to be used. Consequently, we have used the range of the plausible key model runs for formulating advice on stock status.

Research recommendations

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

- Growth / Maturity / Mortality schedules at age. Whereas the work undertaken on swordfish movement since the previous assessment has perhaps narrowed the range of this parameter considered in the assessment, it has been shown to have less affect on model uncertainty than growth/maturity/mortality. Improved knowledge of the growth pattern of swordfish in the south-western Pacific Ocean will be critical to reducing the uncertainty in the estimates of management quantities. Resolving this issue will involve the validation of the ageing process applied, should encompass the age and geographic range of the stock, and take account of the sexual dimorphism in both. In using larger and more comprehensive size data, the next assessment should attempt to estimate growth parameters within the model fit. This could be done perhaps with assumptions on maturity at age or with a specification for a sexual maturity schedule in terms of length rather than age (a feature yet to be developed in the MULTIFAN-CL software framework).
- The improved certainty in this assessment has illustrated the importance of size composition data for swordfish, as seen in the reduction in parameter uncertainty for the period where size data are more available. The continued sampling of weight and length information in the key fisheries is strongly recommended. Work to resolve conflicts within these data from within some fisheries, e.g. Australian size data, is encouraged to ascertain their causes, perhaps by reviewing the sampling protocols for weight and length collections.
- CPUE. The CPUE indices were important for deriving reasonable model estimates in this assessment, in particular for region 2 (DW_2C and SP_2) the consistency in the declining trends and the median sizes caught. We recommend that access be provided to the operational data for the EU_2 catch and effort data because insufficient information was made available to this assessment for adequate standardisation. Specifically, operational factors including the numbers of hooks, numbers of fish landed, use of light sticks, bait type and hook type. This would enable more comprehensive analyses of catch and effort data, particularly variations in targeting and fishing power. 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 swordfish in the model region.
- Selectivity. The next swordfish assessment should explore model sensitivity to the functional forms of the fishery selectivities. 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.
- Sexually dis-aggregated model. To better account for sexual dimorphism and spatial heterogeneity in sex ratios, a modelling approach that includes sexual structure is recommended. Recent developments in MULTIFAN-CL towards this capability may enable the development of a swordfish model with this dimensionality in the future.

8. Acknowledgements

We are grateful for the assistance provided by Peter Williams (SPC) in the preparation of input data-sets for the assessment, and to Robert Campbell (CSIRO), for the supply of size and catch-per-unit effort data, and to Fabrice Bouyé for his assistance with the model computations. We also thank Adam Langley for his useful review of an early draft of this paper.

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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	1N	DW_1N	Longline	CN, CNOS, JPDW, JP, JPOS, KRDW, KR, TWDW, TW, TWOD, TWOS	Number	Hooks	1952-2011
2	1C	DW_1C	Longline	CN, CNOS, JPDW, JP, JPOS, KRDW, KR, TWDW, TW, TWOD, TWOS	Number	Hooks	1953-2011
3	1S	DW_1S	Longline	CN, CNOS, JPDW, JP, JPOS, KRDW, KR, TWDW, TW, TWOD, TWOS	Number	Hooks	1962-2011
4	1N, 1C, 1S	AU_1	Longline	AU	Number	Hooks	1986-2011
5	1N, 1C, 1S	SP_1	Longline	ES	Number	Hooks	2004
6	1N, 1C, 1S	Other_1	Longline	AS, BZ, CK, FM, FJ, PF, GE,GU, IN, ID, KI, MH, NC, NZ, NU, PW, PG, PH, WS, SB, SU, TO, TV, USAS, USMC, USHW, US, VU, VN	Number	Hooks	1983-2011
7	2N	DW_2N	Longline	CN, CNOS, JPDW, JP, JPOS, KRDW, KR, TWDW, TW, TWOD, TWOS	Number	Hooks	1952-2011
8	2C	DW_2C_pre 2001	Longline	CN, CNOS, JPDW, JP, JPOS, KRDW, KR, TWDW, TW, TWOD, TWOS	Number	Hooks	1954-2000
9	2C	DW_2C_post 2001	Longline	CN, CNOS, JPDW, JP, JPOS, KRDW, KR, TWDW, TW, TWOD, TWOS	Number	Hooks	2001-2011
10	2S	DW_2S	Longline	CN, CNOS, JPDW, JP, JPOS, KRDW, KR, TWDW, TW, TWOD, TWOS	Number	Hooks	1958-2009
11	2C, 2S	NZ_2	Longline	NZ	Number	Hooks	1990-2011
12	2N, 2C, 2S	SP_2	Longline	ES	Number	Hooks	2004-2011
13	2N	Other2N	Longline	AS, AU, BZ, CK, FM, FJ, PF, GE,GU, IN, ID, KI, MH, NC, NU, PW, PG, PH, WS, SB, SU, TO, TV, USAS, USMC, USHW, US, VU, VN	Number	Hooks	1982-2011
14	2C	Other_2C	Longline	AS, AU, BZ, CK, FM, FJ, PF, GE,GU, IN, ID, KI, MH, NC, NU, PW, PG, PH, WS, SB, SU, TO, TV, USAS, USMC, USHW, US, VU, VN	Number	Hooks	1982-2011

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

	Length-frequency	**Weight-frequency**
DW_1N	914	52
DW_1C	2,181	0
DW_1S	153	0
AU_1	5,874	311,955
SP_1	444	0
Other_1	2,706	810
DW_2N	35,611	178
DW_2C_pre 2001	2,134	0
DW_2C_post 2001	752	0
DW_2S	515	0
NZ_2	5,264	32,920
SP_2	204,648	0
Other2N	5,655	3,590
Other_2C	3,727	2,505
Total	**270,578**	**352,010**

Table 3. Biological parameters used in the assessment.

Parameter	Value	Comment	Source
Number of age classes	20	Fixed. Pools all fish 20 years and older together in the oldest age class.	2008 assessment.
Length-weight relationship ($L = aW^b$)	a= 3.879 e-07; b= 3.24	Fixed	Davies et al., 2005
Growth parameters (von Bertalanffy)	Hawai'ian estimates:		De Martini. 2007
	Mean length at age 1: 74.83 cm;	Fixed	
	Mean length at age 20+: 242.35 cm;	Fixed	
	k: 0.257 $year^{-1}$	Fixed	
	Australian estimates:		
	Mean length at age 1: 87.34 cm;	Fixed	Young & Drake (2001)
	Mean length at age 20+: 254.10 cm;	Fixed	
	k: 0.102 $year^{-1}$	Fixed	
Natural mortality coefficient	Hawai'ian estimates: 0.31 and 0.38 $year^{-1}$	Fixed	Kolody et al. (2008)
	Australian estimates: 0.16 and 0.20 $year^{-1}$	Fixed	Kolody et al. (2008)
Maturity ogive (females)	Age: 1 to 20+ Hawai'ian estimates: 0 0.02 0.1 0.5 0.9 0.98 1 1 1 1 1 1 1 1 1 1 1 1 1	Fixed	Kolody et al. (2008)
	Australian estimates: 0.012 0.023 0.041 0.068 0.108 0.162 0.229 0.307 0.389 0.472 0.550 0.620 0.680 0.731 0.773 0.808 0.836 0.859 0.878	Fixed	Kolody et al. (2008)
Beverton-Holt stock-recruitment relationship - steepness	0.8 Sensitivity: 0.65, 0.95	Fixed	

Table 4. Definitions of the eight assumed combinations for growth, maturity and mortality schedules based upon the two growth rate estimates (Australian and Hawai'ian), mortality coefficients, and spawner effects on mortality. Each combination of four are termed the Hawai'ian and Australian 'schedules'

Schedule	Growth	Maturity at age	Mortality at age
GAMH	Slow (AU)	50% age 10	High
GAMHS	Slow (AU)	50% age 10	High + spawner effect
GAML	Slow (AU)	50% age 10	Low
GAMLS	Slow (AU)	50% age 10	Low + spawner effect
GHMH	Fast (HW)	50% age 4	High
GHMHS	Fast (HW)	50% age 4	High + spawner effect
GHML	Fast (HW)	50% age 4	Low
GHMLS	Fast (HW)	50% age 4	Low + spawner effect

Table 5. 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 the first quarter of each year. Annual variation in the proportions of recruitment to each region was estimated. Recruitment is weakly related to spawning biomass with no lag period 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	20 annual age-classes, with the last representing a 20+ 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. Splines (with 4 nodes) were assumed for most fisheries, with non-decreasing selectivities assumed for fisheries 3, 8, 9, 10, and 12. The coefficients for age-classes above age 9 years were constrained to be equal for the non-decreasing selectivities.
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	Fisheries for which the CPUE index is fitted, the effort deviations are constrained by a temporally-variable penalty weight based upon the index coefficient of variation (constrained to have a mean of 0.2). For other fisheries, variability of effort deviations was constrained by a penalty weight scaled by the square root of the effort.
Natural mortality	Constant according to the eight assumed schedules in Table 3 and Table 4
Movement	Quarterly and assumed constant at a diffusion rate of 0.11, with sensitivities of 0.0, 0.05 and 0.25.

Table 6. Reference case (Ref.case) model assumptions and sensitivity analyses as recommended by the Pre-Assessment Workshop, (OFP 2013) making up the sixteen key model runs for the swordfish assessment.

Assumption	Ref. case	Sensitivities	
Steepness	0.8	0.65; 0.95	
Movement (diffusion rate)	0.11	0.0; 0.05; 0.25	
Growth rate / maturity / mortality schedule	GHMHS	GHMH GHML GHMLS	GAMHS GAMH GAML GAMLS
CPUE series	Region 1: DW_1C, AU_1 Region 2: DW_2C; EU_2	Region 1: DW_1C, AU_1 Region 2 options: 3. DW_2C only 4. DW_2C, NZ_2	
Size data relative weighting	AU, NZ = nsamp/40; Other = nsamp/100	AU, NZ = nsamp/80; Other = nsamp/200	

Table 7: Names and descriptions of the key model runs undertaken for the 2013 swordfish assessment. The Reference case is in bold and all other runs are one-off sensitivities to the Reference case.

Run name	**Description**
GHMHS **(Ref.case)**	Steepness = 0.8; Movement diffusion rate = 0.11; GHMHS growth/maturity/mortality option; Fit to DW_1C, AU_1, DW_2C pre- and post-2001, EU_2 CPUE indices; size data relative weight is AU/NZ: n/40, Other: n/100.
GHMH	Assume GHMH growth/maturity/mortality option
GHML	Assume GHML growth/maturity/mortality option
GHMLS	Assume GHMLS growth/maturity/mortality option
GAMH	Assume GAMH growth/maturity/mortality option
GAMHS	Assume GAMHS growth/maturity/mortality option
GAML	Assume GAML growth/maturity/mortality option
GAMLS	Assume GAMLS growth/maturity/mortality option
cpopt_CP2_TW	For region 2, fit only to DW_1C CPUE index (exclude EU_2 index from fit)
cpopt_CP2_TW_NZ	For region 2, fit to DW_1C and NZ_2 CPUE index (replace EU_2 index)
steep_0.65	Assume stock-recruitment relationship steepness = 0.65
steep_0.95	Assume stock-recruitment relationship steepness = 0.95
mvmnt_0	Assume no movement among regions
mvmnt_0.05	Assume a movement diffusion rate = 0.05
mvmnt_0.25	Assume a movement diffusion rate = 0.25
sz_wt_80_200	Low size data relative weight is AU/NZ: n/80, Other: n/200.

Table 8: 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

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[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 9: 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).

	Ref.case (GHMHS)	GHMH	GHML	GHMLS	GAMH	GAMHS	GAML	GAMLS
$C_{current}$	10205	10342	10507	10376	10361	10592	10708	10870
C_{latest}	9990	10108	10156	10052	9702	9782	9873	9852
$Y_{F_{current}}$	8603	9141	8355	7898	5946	6923	4067	5169
$Y_{F_{MSY}}$ or MSY	10420	12550	9228	8375	6081	6938	5299	5764
$Y_{F_{current}}/MSY$	0.826	0.728	0.905	0.943	0.978	0.998	0.768	0.897
$C_{current}/MSY$	0.979	0.824	1.139	1.239	1.704	1.527	2.021	1.886
C_{latest}/MSY	0.959	0.805	1.101	1.2	1.595	1.41	1.863	1.709
F_{MSY}	0.173	0.159	0.152	0.159	0.089	0.092	0.081	0.084
F_{mult}	1.98	2.505	1.608	1.426	0.824	0.942	0.566	0.684
$F_{current}/F_{MSY}$	0.505	0.399	0.622	0.701	1.213	1.061	1.766	1.463
B_0	151500	183900	154900	140000	168600	189900	171600	184400
B_{MSY}	60290	78860	60680	52530	68350	75100	65680	69010
B_{MSY}/B_0	0.398	0.429	0.392	0.375	0.405	0.395	0.383	0.374
$B_{current}$	94992	124516	92420	79241	91202	102947	75623	87922
B_{latest}	93728	123095	89187	75942	86984	95881	68974	77604
$B_{F_{current}}$	92980	127100	84270	69310	57140	71130	31450	43720
$B_{current_{F=0}}$	140216	166321	145749	135311	172221	186052	178963	190079
$B_{latest_{F=0}}$	141506	167445	146850	136350	177221	188724	185488	194533
SB_0	85510	92500	93520	89740	68580	77290	84310	89150
SB_{MSY}	20150	19870	21230	21860	14890	17500	19500	21190
SB_{MSY}/SB_0	0.236	0.215	0.227	0.244	0.217	0.226	0.231	0.238
$SB_{current}$	43678	50490	43580	40745	23449	31461	22462	31197
SB_{latest}	37888	44072	36412	33832	17822	23386	15751	22120
$SB_{F_{current}}$	40900	49000	36760	33270	10970	16000	6393	10670
$SB_{current_{F=0}}$	79535	84393	88406	86979	69130	76903	85174	90434
$SB_{latest_{F=0}}$	75846	80277	85150	83776	68931	74904	86331	91196
$B_{current}/B_0$	0.627	0.677	0.597	0.566	0.541	0.542	0.441	0.477
B_{latest}/B_0	0.619	0.669	0.576	0.542	0.516	0.505	0.402	0.421
$B_{F_{current}}/B_0$	0.614	0.691	0.544	0.495	0.339	0.375	0.183	0.237
$B_{current}/B_{MSY}$	1.576	1.579	1.523	1.508	1.334	1.371	1.151	1.274
B_{latest}/B_{MSY}	1.555	1.561	1.47	1.446	1.273	1.277	1.05	1.125
$B_{F_{current}}/B_{MSY}$	1.542	1.612	1.389	1.319	0.836	0.947	0.479	0.634
$B_{current}/B_{current_{F=0}}$	0.677	0.749	0.634	0.586	0.53	0.553	0.423	0.463
$B_{latest}/B_{latest_{F=0}}$	0.662	0.735	0.607	0.557	0.491	0.508	0.372	0.399
$SB_{current}/SB_0$	0.511	0.546	0.466	0.454	0.342	0.407	0.266	0.35
SB_{latest}/SB_0	0.443	0.476	0.389	0.377	0.26	0.303	0.187	0.248
$SB_{F_{current}}/SB_0$	0.478	0.53	0.393	0.371	0.16	0.207	0.076	0.12
$SB_{current}/SB_{MSY}$	2.168	2.541	2.053	1.864	1.575	1.798	1.152	1.472
SB_{latest}/SB_{MSY}	1.88	2.218	1.715	1.548	1.197	1.336	0.808	1.044
$SB_{F_{current}}/SB_{MSY}$	2.03	2.466	1.732	1.522	0.737	0.914	0.328	0.504
$SB_{curr}/SB_{curr_{F=0}}$	0.549	0.598	0.493	0.468	0.339	0.409	0.264	0.345
$SB_{latest}/SB_{latest_{F=0}}$	0.5	0.549	0.428	0.404	0.259	0.312	0.182	0.243
Steepness (h)	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8

Table 9 cont.

	Ref.case (GHMHS)	cpopt_CP2_TW	cpopt_CP2_TW_NZ	steep_0.65	steep_0.95	sz_wt_80_200
$C_{current}$	10205	10170	10326	10205	10205	10294
C_{latest}	9990	9891	10304	9990	9990	10200
$Y_{F_{current}}$	8603	8409	8384	7943	8977	8771
$Y_{F_{MSY}}$ or MSY	10420	9647	19640	8506	12730	11140
$Y_{F_{current}}/MSY$	0.826	0.872	0.427	0.934	0.705	0.787
$C_{current}/MSY$	0.979	1.054	0.526	1.2	0.802	0.924
C_{latest}/MSY	0.959	1.025	0.525	1.174	0.785	0.916
F_{MSY}	0.173	0.173	0.174	0.129	0.248	0.172
F_{mult}	1.98	1.764	5.218	1.427	3.033	2.182
$F_{current}/F_{MSY}$	0.505	0.567	0.192	0.701	0.33	0.458
B_0	151500	139600	288800	153800	149800	162400
B_{MSY}	60290	55800	113200	66030	51380	64920
B_{MSY}/B_0	0.398	0.4	0.392	0.429	0.343	0.4
$B_{current}$	94992	84657	255276	94871	94870	105213
B_{latest}	93728	83458	286865	93617	93616	104117
$B_{F_{current}}$	92980	81210	237600	85760	96920	104100
$B_{current_{F=0}}$	140216	129835	300730	140088	140087	150422
$B_{latest_{F=0}}$	141506	131087	335022	141387	141387	151788
SB_0	85510	78780	163100	86800	84560	91640
SB_{MSY}	20150	18600	37810	25850	12350	21770
SB_{MSY}/SB_0	0.236	0.236	0.232	0.298	0.146	0.238
$SB_{current}$	43678	37839	128222	43609	43608	49187
SB_{latest}	37888	32052	134259	37827	37826	42973
$SB_{F_{current}}$	40900	34500	122900	37710	42620	46950
$SB_{current_{F=0}}$	79535	73664	164460	79461	79460	85158
$SB_{latest_{F=0}}$	75846	69802	172884	75777	75776	80821
$B_{current}/B_0$	0.627	0.606	0.884	0.617	0.633	0.648
B_{latest}/B_0	0.619	0.598	0.993	0.609	0.625	0.641
$B_{F_{current}}/B_0$	0.614	0.582	0.823	0.558	0.647	0.641
$B_{current}/B_{MSY}$	1.576	1.517	2.255	1.437	1.846	1.621
B_{latest}/B_{MSY}	1.555	1.496	2.534	1.418	1.822	1.604
$B_{F_{current}}/B_{MSY}$	1.542	1.455	2.099	1.299	1.886	1.604
$B_{current}/B_{current_{F=0}}$	0.677	0.652	0.849	0.677	0.677	0.699
$B_{latest}/B_{latest_{F=0}}$	0.662	0.637	0.856	0.662	0.662	0.686
$SB_{current}/SB_0$	0.511	0.48	0.786	0.502	0.516	0.537
SB_{latest}/SB_0	0.443	0.407	0.823	0.436	0.447	0.469
$SB_{F_{current}}/SB_0$	0.478	0.438	0.754	0.434	0.504	0.512
$SB_{current}/SB_{MSY}$	2.168	2.034	3.391	1.687	3.531	2.259
SB_{latest}/SB_{MSY}	1.88	1.723	3.551	1.463	3.063	1.974
$SB_{F_{current}}/SB_{MSY}$	2.03	1.855	3.25	1.459	3.451	2.157
$SB_{curr}/SB_{curr_{F=0}}$	0.549	0.514	0.78	0.549	0.549	0.578
$SB_{latest}/SB_{latest_{F=0}}$	0.5	0.459	0.777	0.499	0.499	0.532
Steepness (h)	0.8	0.8	0.8	0.65	0.95	0.8

Table 9 cont.

	Ref.case (GHMHS)	mvmnt_0	mvmnt_0.05	mvmnt_0.25	Grid median	Grid 5%ile	Grid 95%ile
$C_{current}$	10205	9728	10254	10218	10453	9958	11393
C_{latest}	9990	9483	10101	9816	10069	9690	10650
$Y_{F_{current}}$	8603	7900	8270	9347	7839	3380	9350
$Y_{F_{MSY}}$ or MSY	10420	8637	10290	12110	8417	5133	16560
$Y_{F_{current}}/MSY$	0.826	0.915	0.804	0.772	0.888	0.412	0.999
$C_{current}/MSY$	0.979	1.126	0.996	0.844	1.241	0.628	2.13
C_{latest}/MSY	0.959	1.098	0.982	0.811	1.2	0.616	1.996
F_{MSY}	0.173	0.174	0.173	0.172	0.122	0.06	0.232
F_{mult}	1.98	1.544	2.093	2.247	1.422	0.554	4.423
$F_{current}/F_{MSY}$	0.505	0.648	0.478	0.445	0.703	0.226	1.806
B_0	151500	124000	149600	177800	184500	138500	291300
B_{MSY}	60290	49790	59500	70340	70600	49190	111300
B_{MSY}/B_0	0.398	0.402	0.398	0.396	0.389	0.313	0.437
$B_{current}$	94992	74982	100635	108446	104201	79241	223842
B_{latest}	93728	79050	99775	107451	103009	75578	228322
$B_{F_{current}}$	92980	67600	94040	115100	83920	31280	202600
$B_{current_{F=0}}$	140216	118743	145850	153727	185481	133330	290824
$B_{latest_{F=0}}$	141506	125425	147714	155232	193251	136088	315410
SB_0	85510	70740	84420	100300	92330	70730	150800
SB_{MSY}	20150	16670	19860	23610	21000	9865	36860
SB_{MSY}/SB_0	0.236	0.236	0.235	0.235	0.227	0.121	0.298
$SB_{current}$	43678	32650	46471	51360	43494	23118	104005
SB_{latest}	37888	31614	41182	44596	36743	18170	104704
$SB_{F_{current}}$	40900	27750	41950	52380	32550	6481	93530
$SB_{current_{F=0}}$	79535	67651	82333	87281	89419	69130	153305
$SB_{latest_{F=0}}$	75846	69080	79347	82651	89589	69794	155622
$B_{current}/B_0$	0.627	0.605	0.673	0.61	0.608	0.456	0.806
B_{latest}/B_0	0.619	0.638	0.667	0.604	0.59	0.414	0.9
$B_{F_{current}}/B_0$	0.614	0.545	0.629	0.647	0.487	0.155	0.762
$B_{current}/B_{MSY}$	1.576	1.506	1.691	1.542	1.589	1.169	2.237
B_{latest}/B_{MSY}	1.555	1.588	1.677	1.528	1.553	1.072	2.395
$B_{F_{current}}/B_{MSY}$	1.542	1.358	1.581	1.636	1.29	0.376	1.998
$B_{current}/B_{current_{F=0}}$	0.677	0.631	0.69	0.705	0.626	0.452	0.801
$B_{latest}/B_{latest_{F=0}}$	0.662	0.63	0.675	0.692	0.602	0.395	0.81
$SB_{current}/SB_0$	0.511	0.462	0.55	0.512	0.481	0.295	0.706
SB_{latest}/SB_0	0.443	0.447	0.488	0.445	0.417	0.214	0.706
$SB_{F_{current}}/SB_0$	0.478	0.392	0.497	0.522	0.345	0.075	0.657
$SB_{current}/SB_{MSY}$	2.168	1.959	2.34	2.175	2.168	1.14	4.716
SB_{latest}/SB_{MSY}	1.88	1.896	2.074	1.889	1.88	0.862	4.295
$SB_{F_{current}}/SB_{MSY}$	2.03	1.665	2.112	2.219	1.539	0.283	4.144
$SB_{curr}/SB_{curr_{F=0}}$	0.549	0.483	0.564	0.588	0.502	0.303	0.719
$SB_{latest}/SB_{latest_{F=0}}$	0.5	0.458	0.519	0.54	0.447	0.218	0.692
Steepness (h)	0.8	0.8	0.8	0.8	0.8	-	-

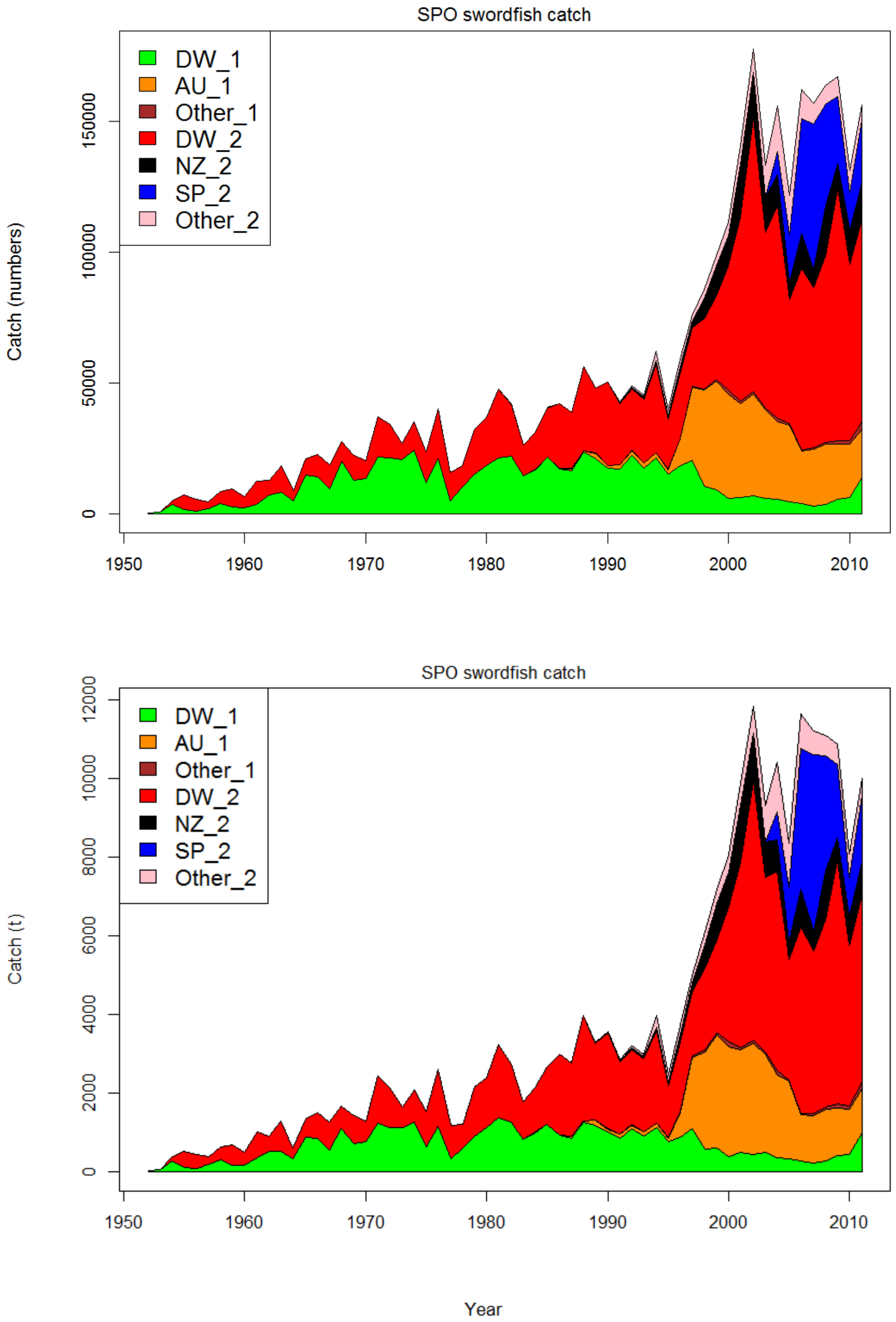


Figure 1. Total swordfish catches (numbers top, weight bottom) grouped by major longline-method fisheries in the model regions, 1952–2011: DW_1 - distant water fleet region 1; AU1 – Australian region 1; Other_1 - Other fisheries region 1; DW_2 - distant water fleet region 2; NZ_2 - New Zealand region 2; SP_2 - Spanish region 2; Other_2 - other fisheries region 2.

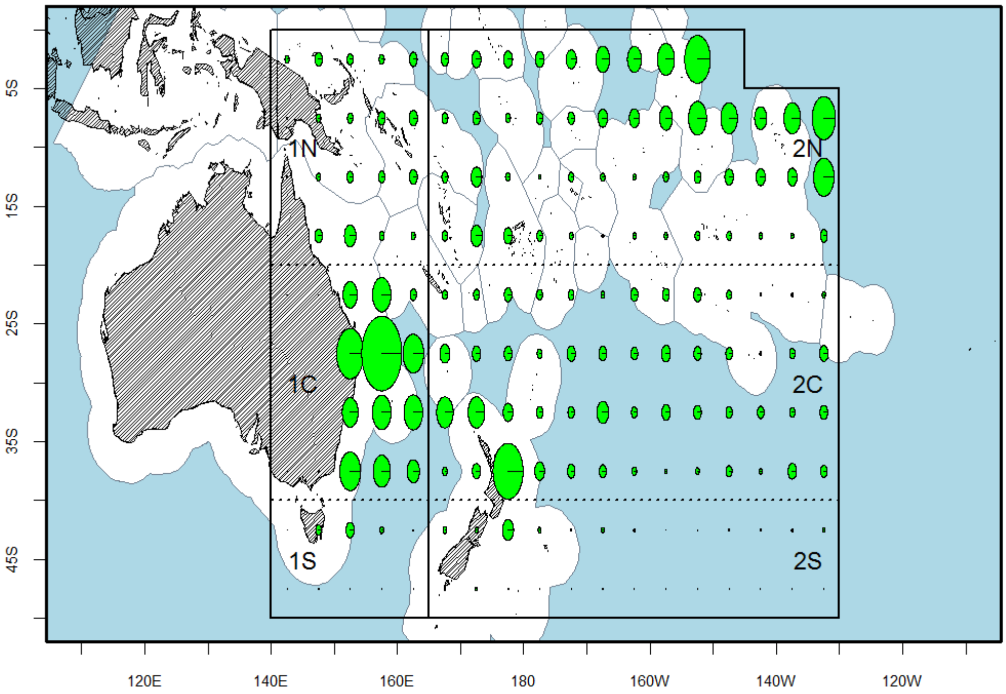


Figure 2. Catches of swordfish (numbers) in the southwest Pacific, 1952–2011. Source: raised catch estimates available from the SPC. The black lines represent the boundaries of the assessment regions 1 and 2 (outer lines) for swordfish in the southwest Pacific Ocean, and the six fishery sub-areas within those regions.

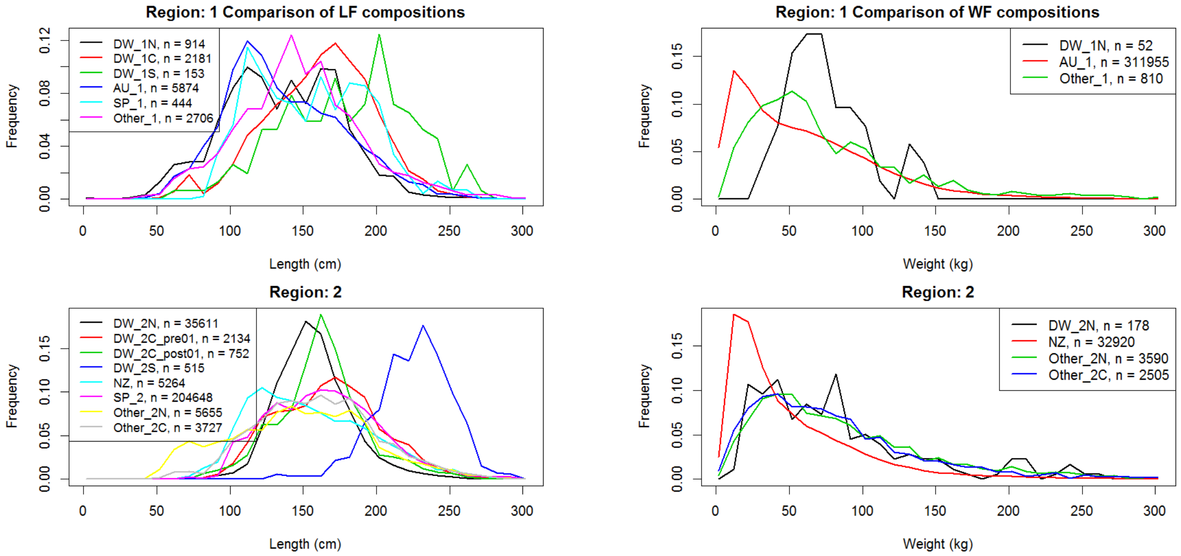


Figure 3. A comparison of the length (centimetres, left) and weight (whole weight, kilogrammes, right) frequency distributions of the sampled catches from the key fisheries, by model region, all years combined.

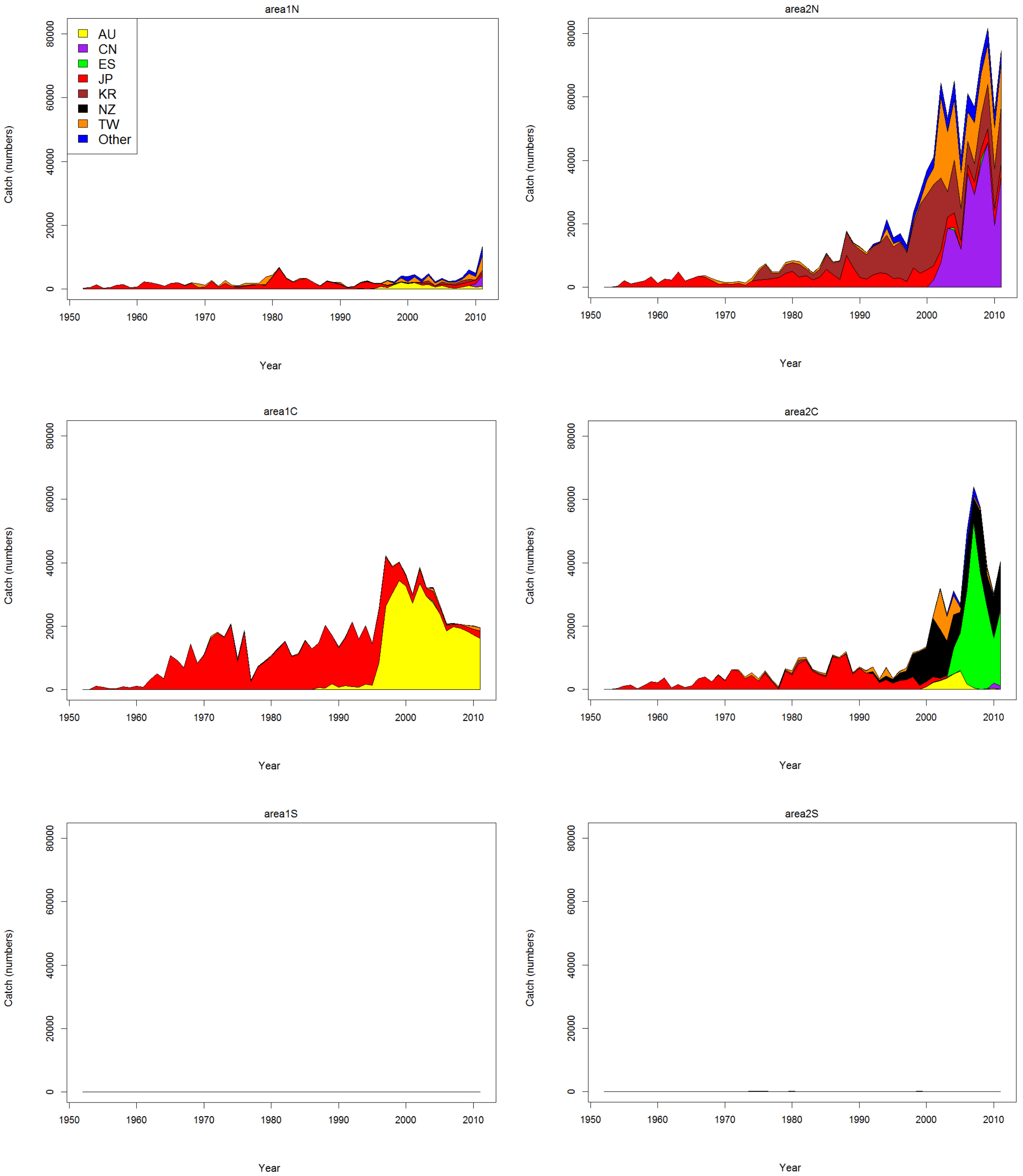


Figure 4. Total estimated catches of swordfish (numbers) by major flag and fishery sub-area from the assessment model for the southwest Pacific, 1952–2011.

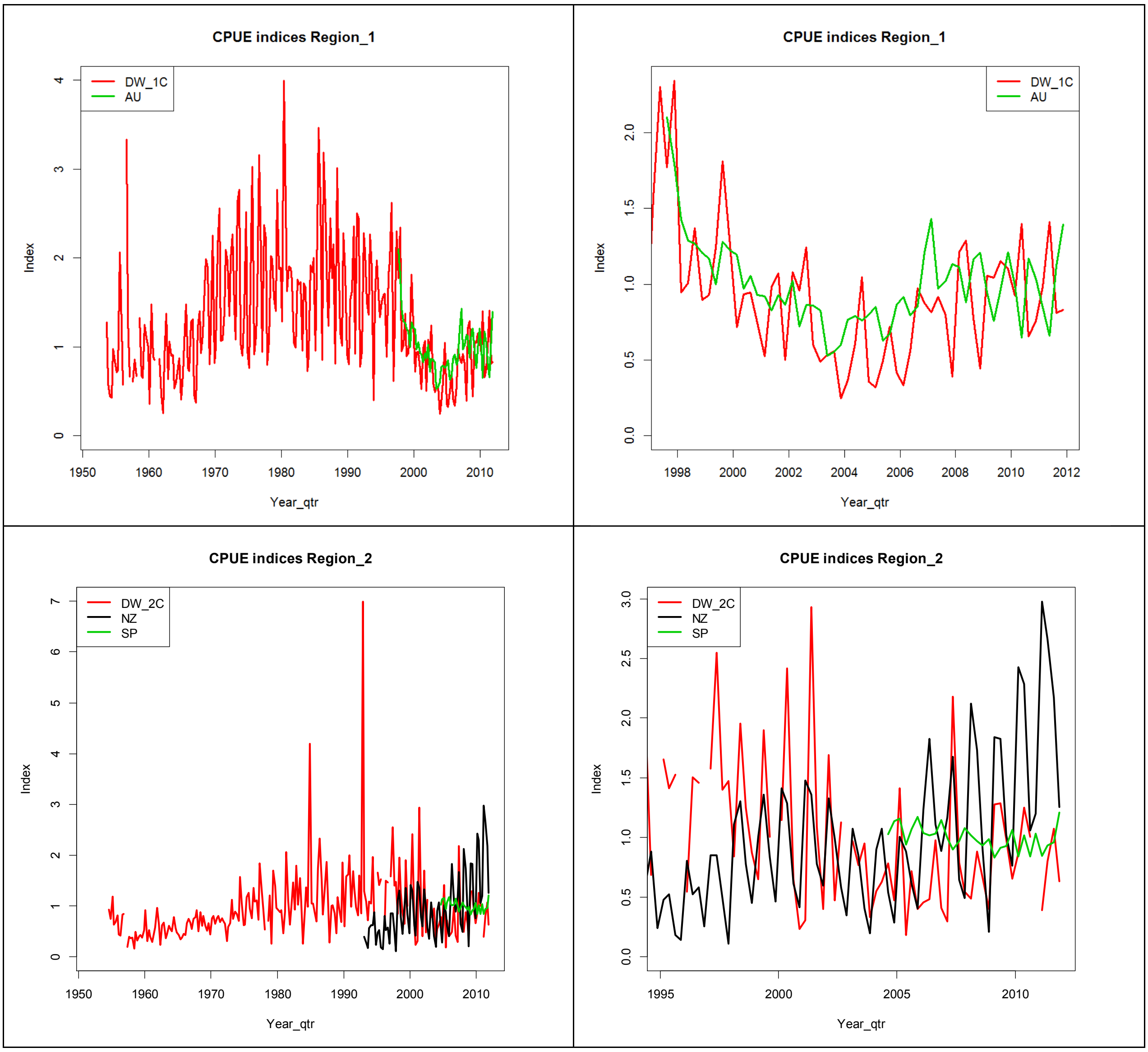


Figure 5. A comparison of the main CPUE indices for five of the fourteen fisheries included in the model. The CPUE series are normalised to the mean of each series.

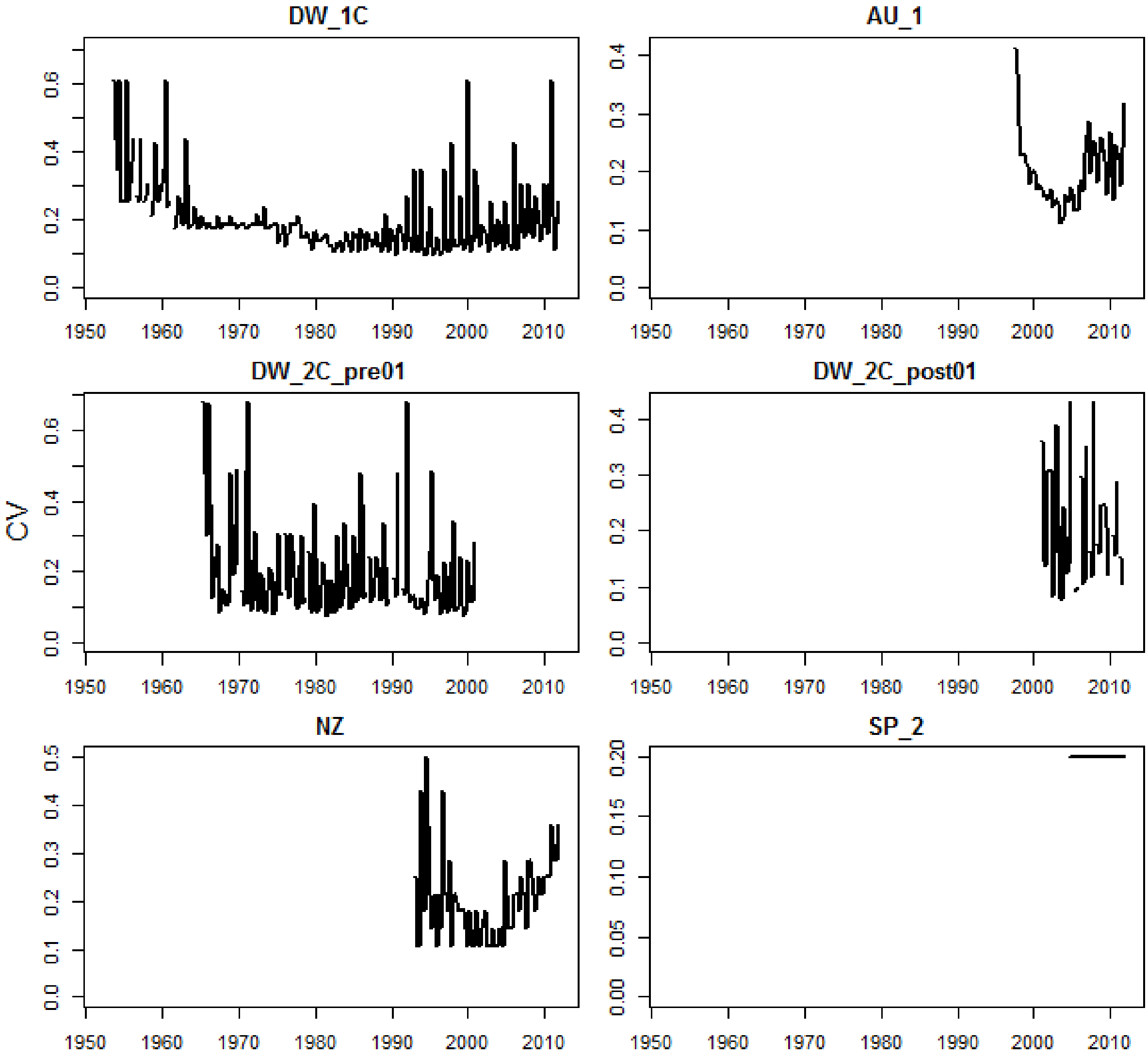


Figure 6: Temporal variation in precision (CV) of standardised CPUE indices for the nine fisheries defined in the model.

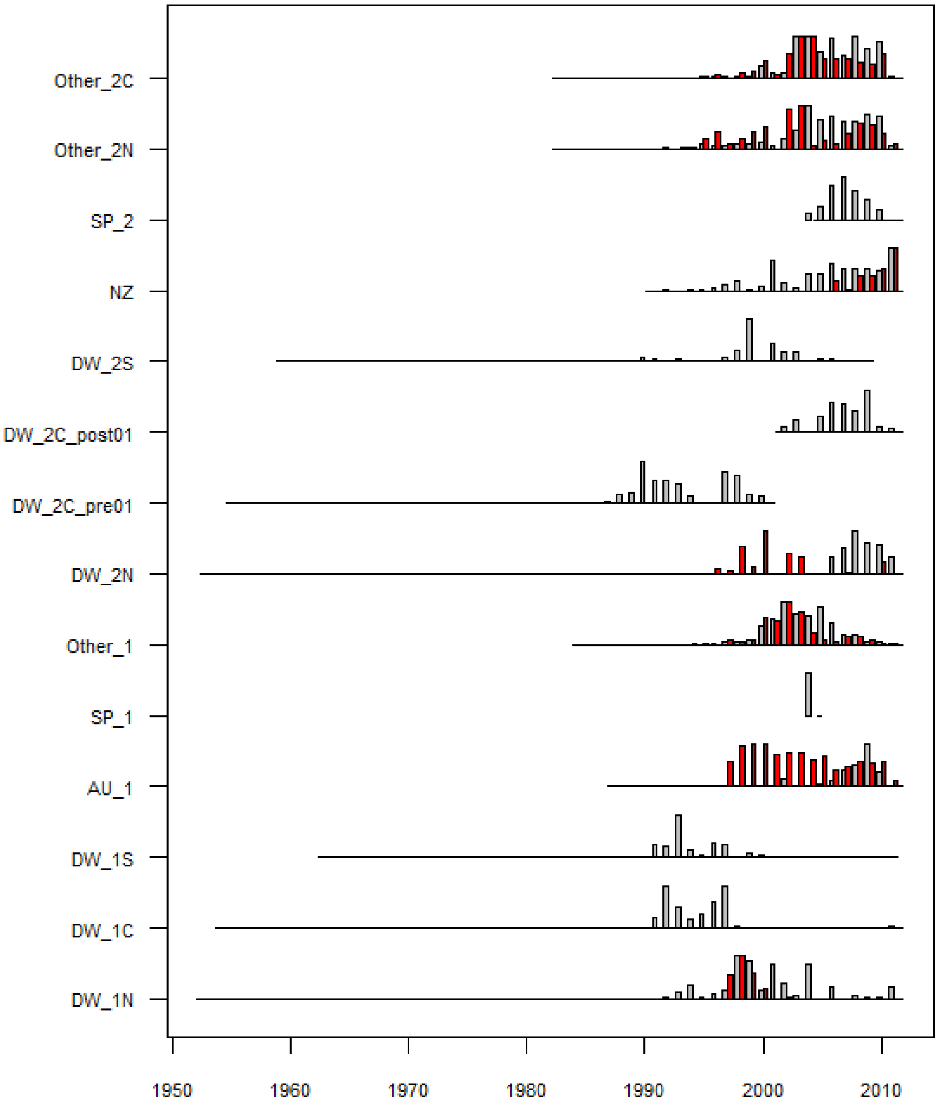


Figure 7: Number of fish size measurements by year for each fishery. The grey bars represent length measurements and the red bars represent weight measurements. The bars represent proportions of the maximum sample size within each fishery. The extent of the horizontal lines indicates the period over which each fishery occurred. Total sample sizes are detailed in Table 2 by fishery.

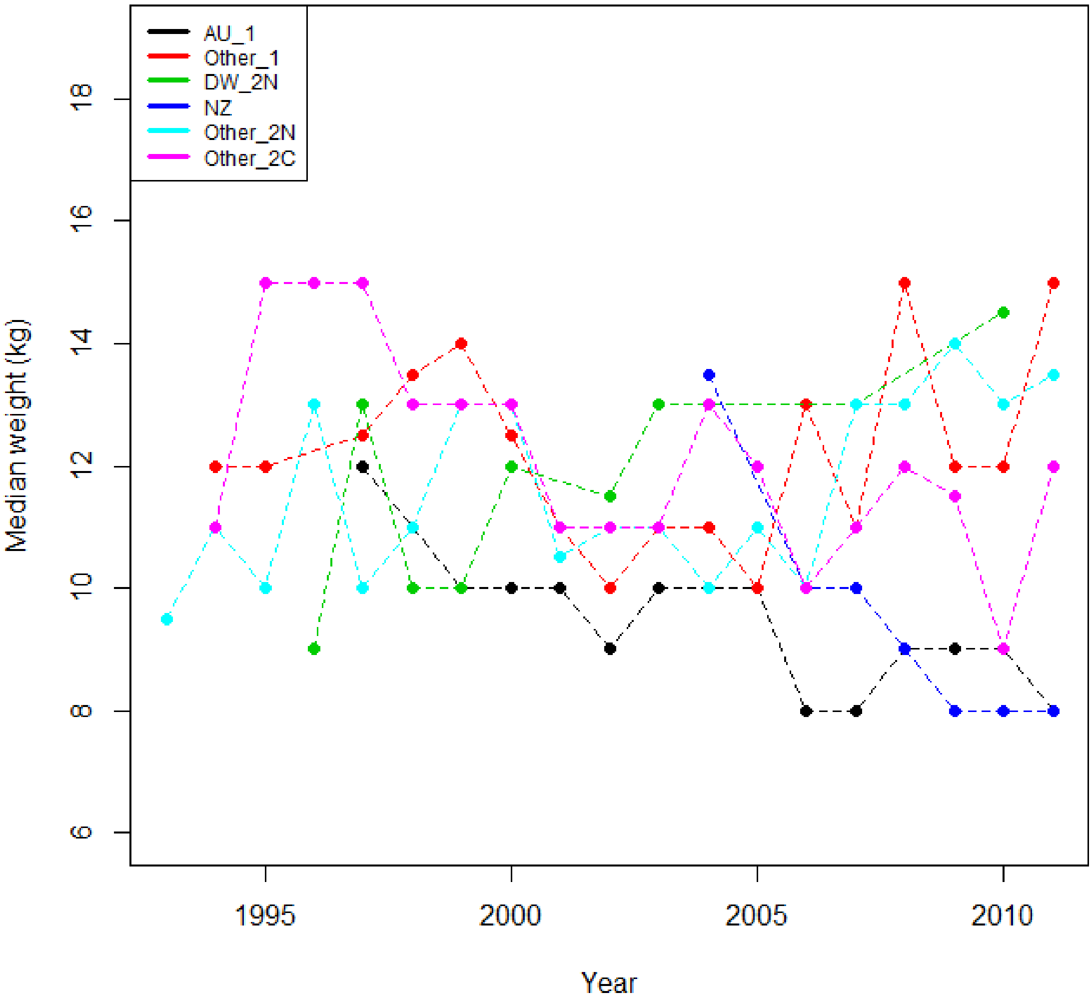


Figure 8: Trends in median fish weight (whole weight, kilogrammes) by year for the main fisheries providing size frequency data. Only years with at least 30 sampled fish are presented.

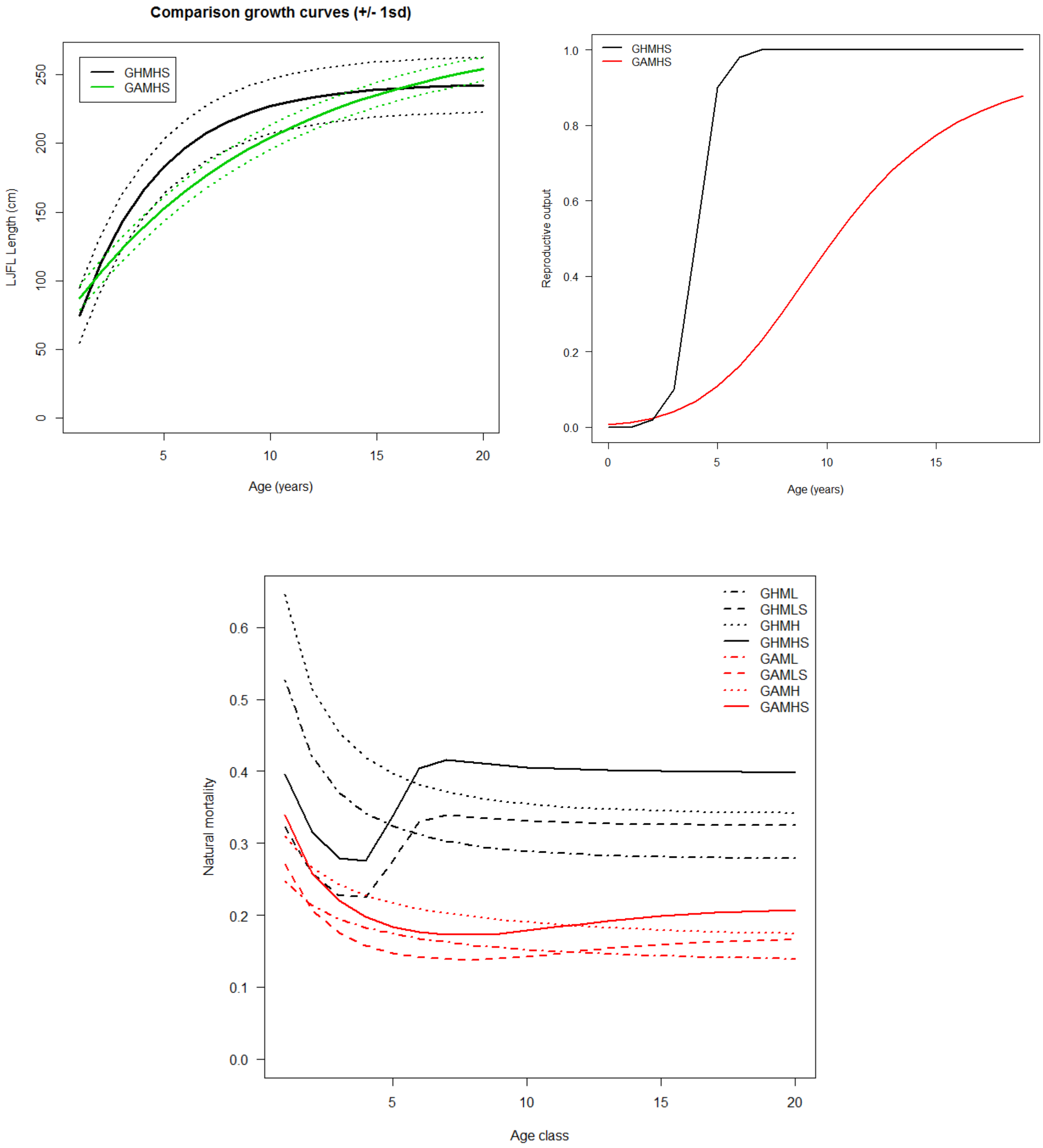


Figure 9: Growth (top left), maturity (top right) and natural mortality (bottom) assumptions used in the 2008 assessment, and for the assessment presented here.

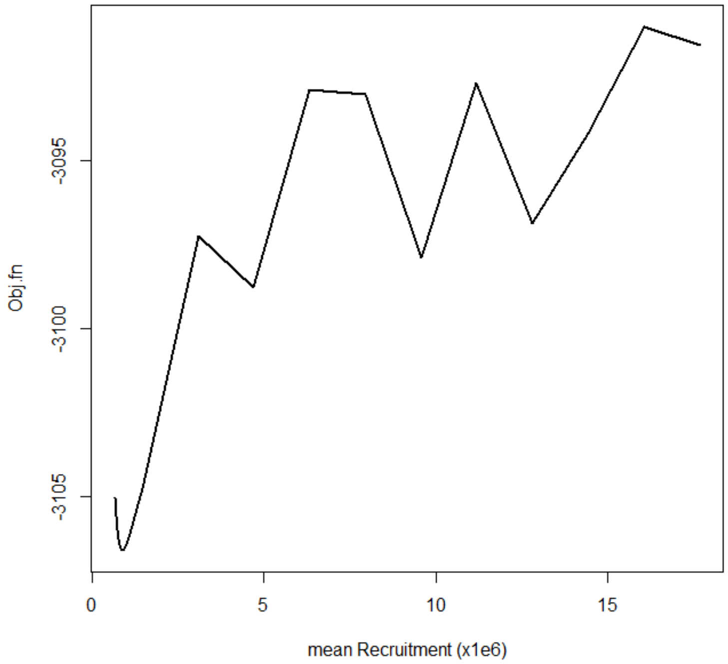


Figure 10: Likelihood profile with respect to the mean recruitment scaling parameter for the reference case model (Ref.case).

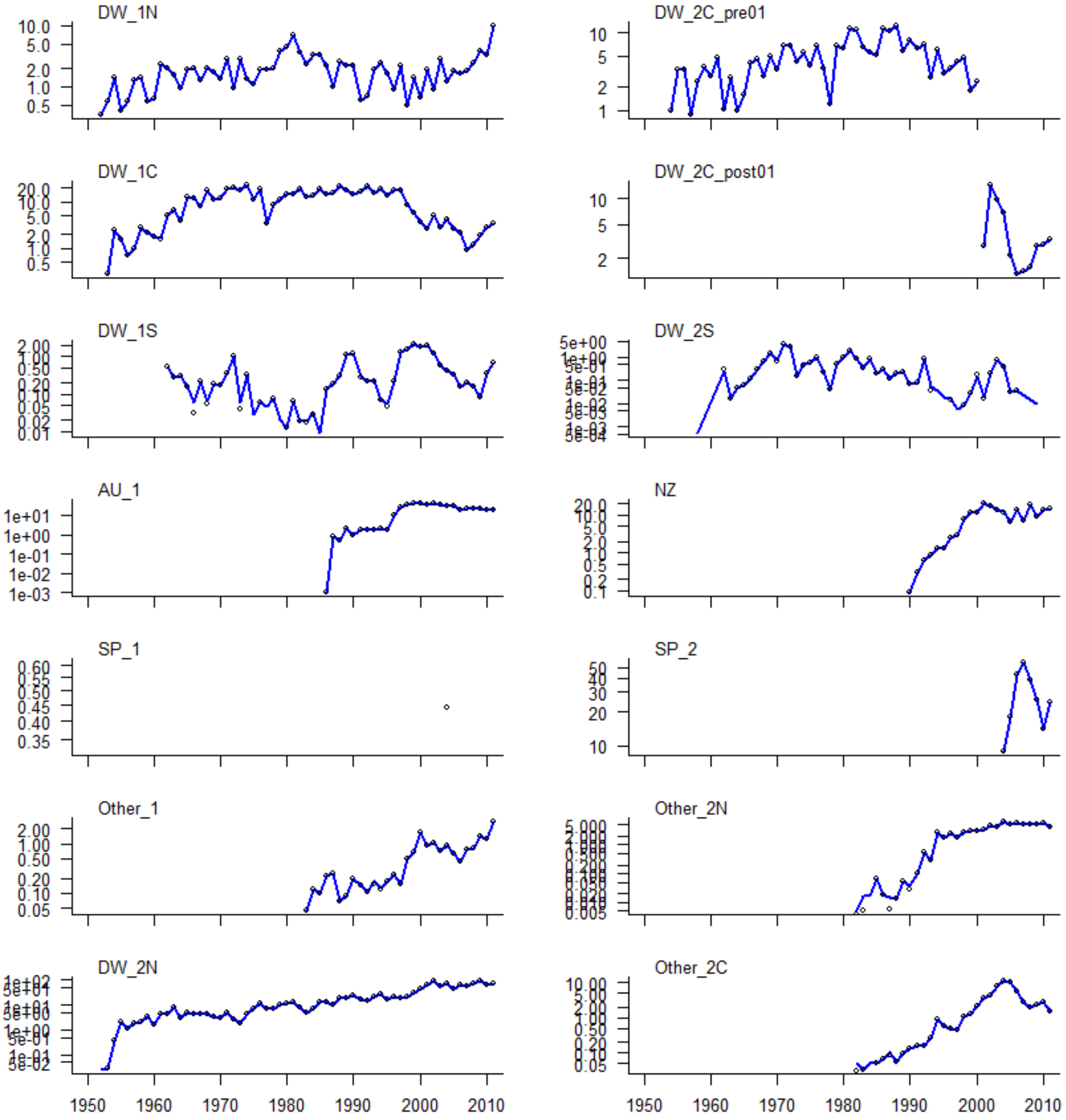


Figure 11: Observed (points) and Ref.case model predicted (blue line) annual catches, by fishery. Catches are expressed as number of fish. The y-axes are plotted on a logarithmic scale.

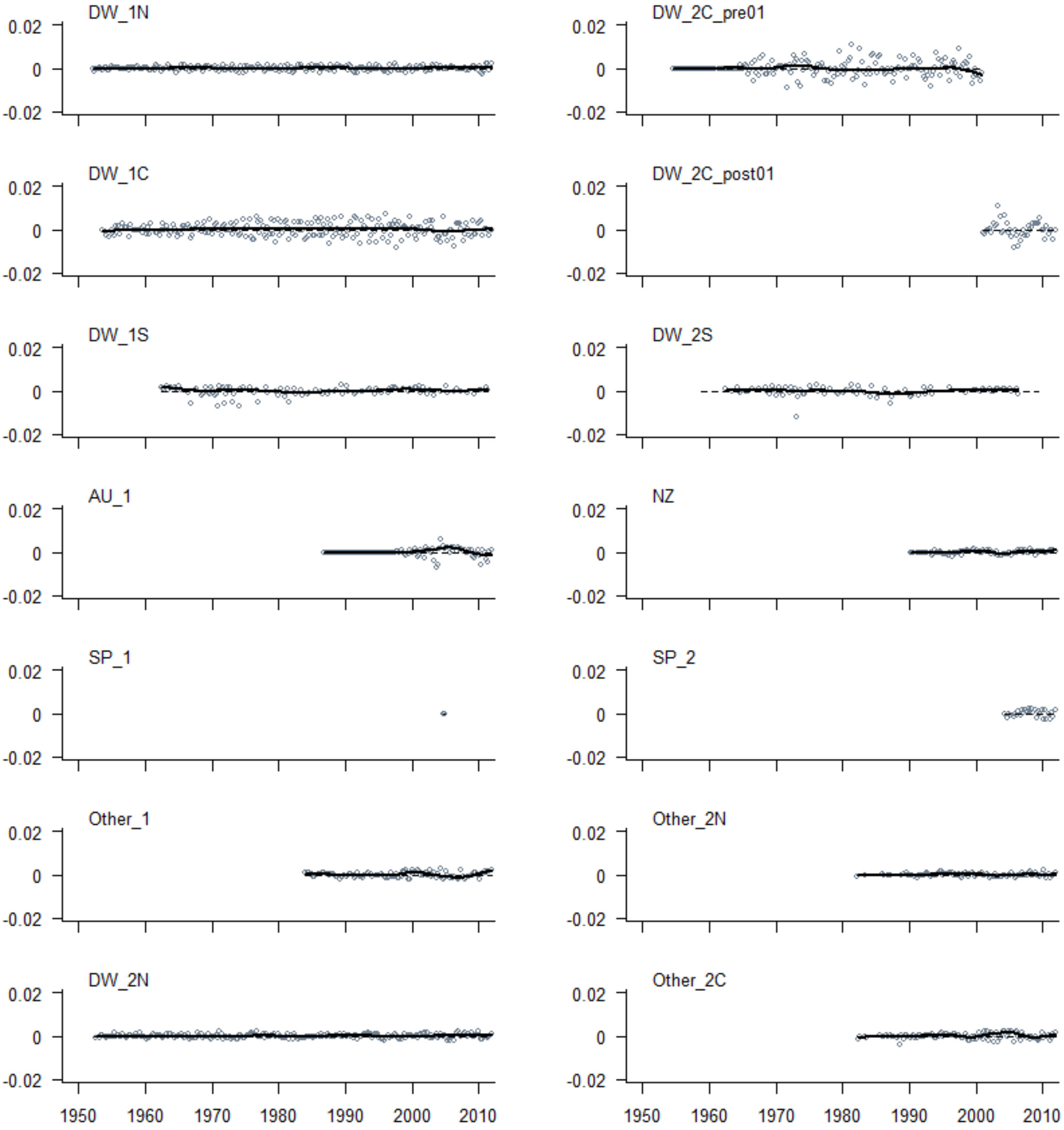


Figure 12: Residuals (ln) of total catch for each fishery from the Ref.case model fit. Solid lines represent lowess fits to the data.

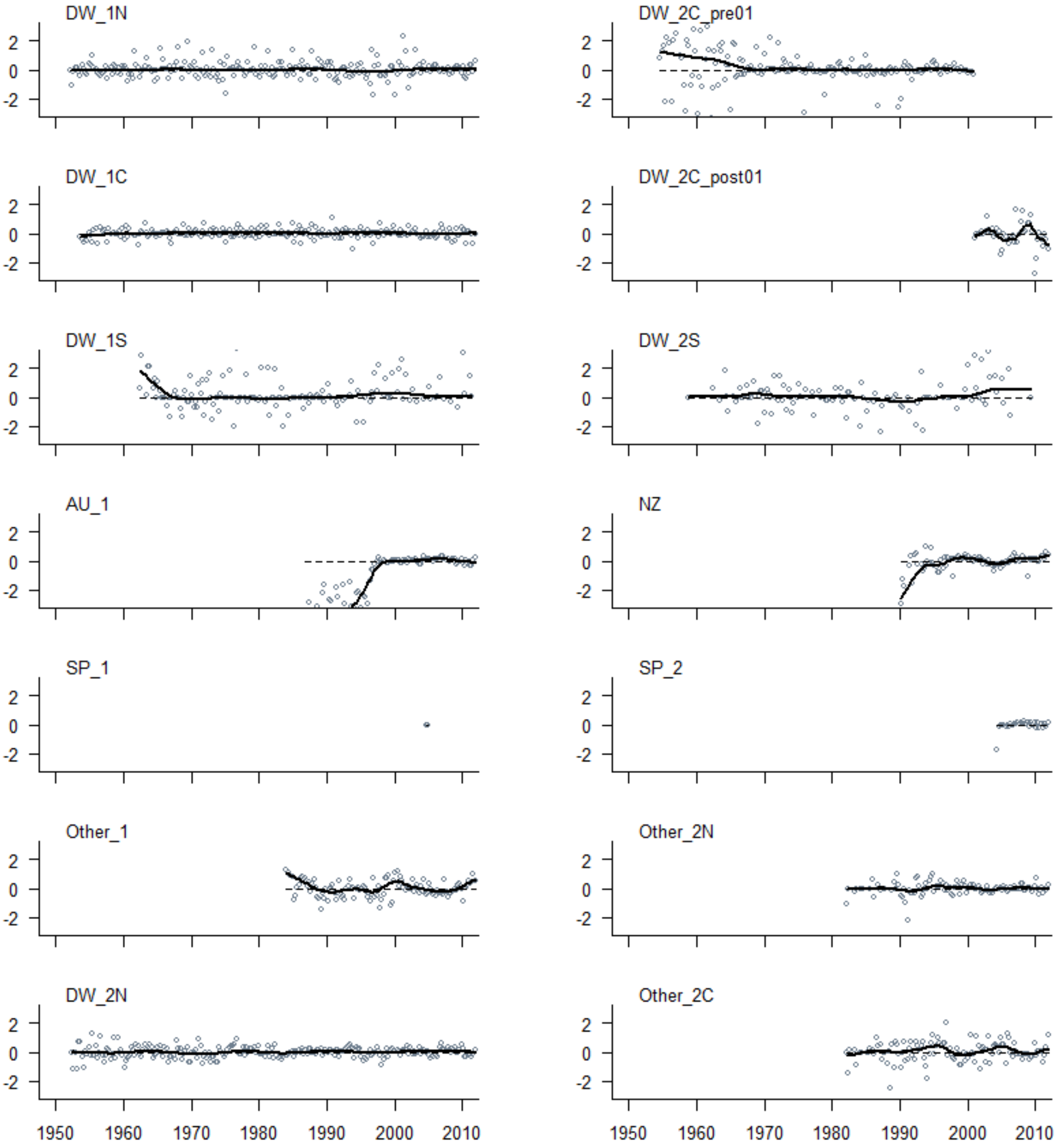


Figure 13: Effort deviations by time period for each fishery. Solid lines represent lowess fits to the data. Model estimates are from the Ref.case model.

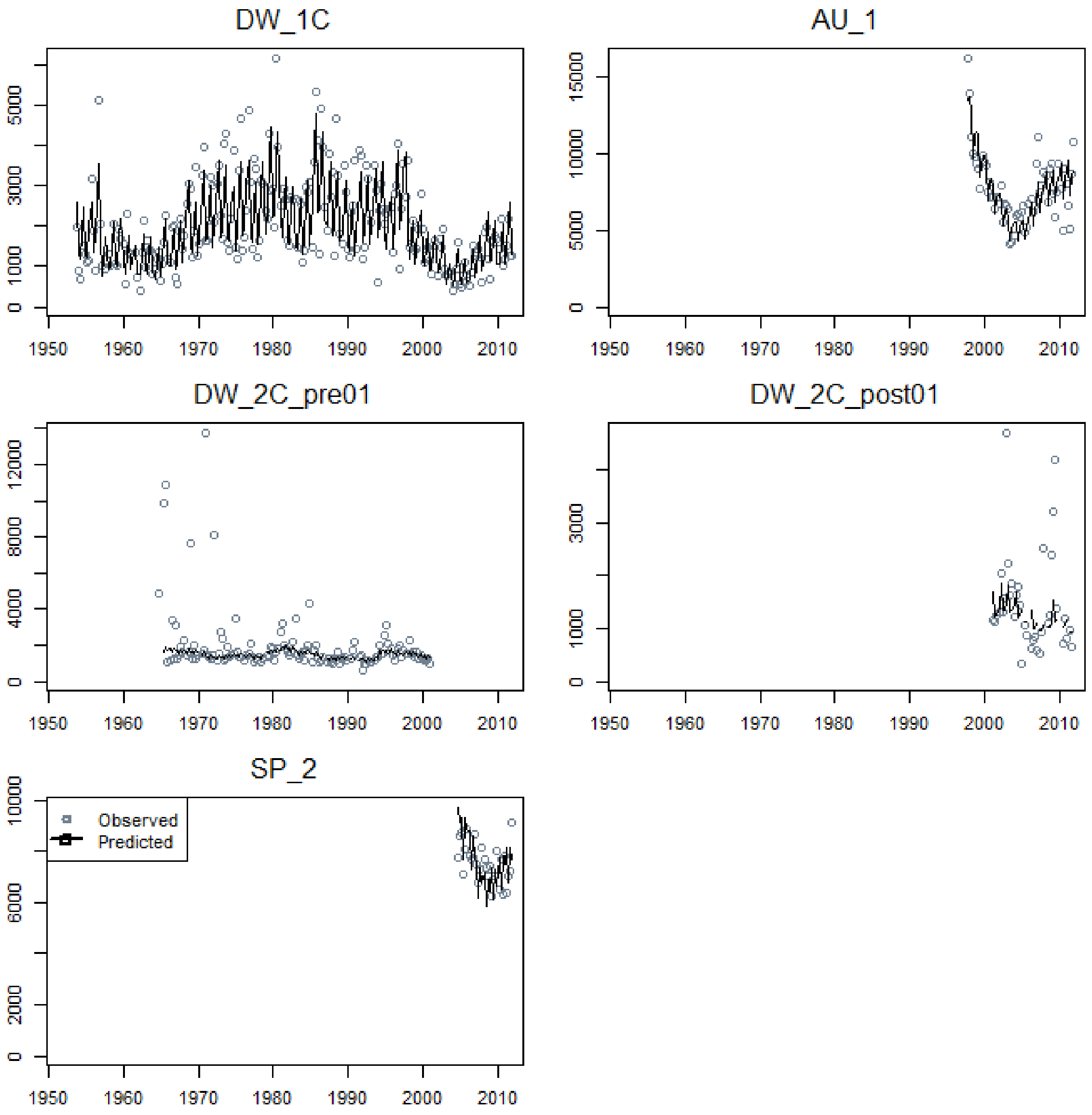


Figure 14: A comparison between observed CPUE (points) and fishery specific exploitable biomass (line) for the main fisheries included in the model. Model estimates are from the Ref.case model.

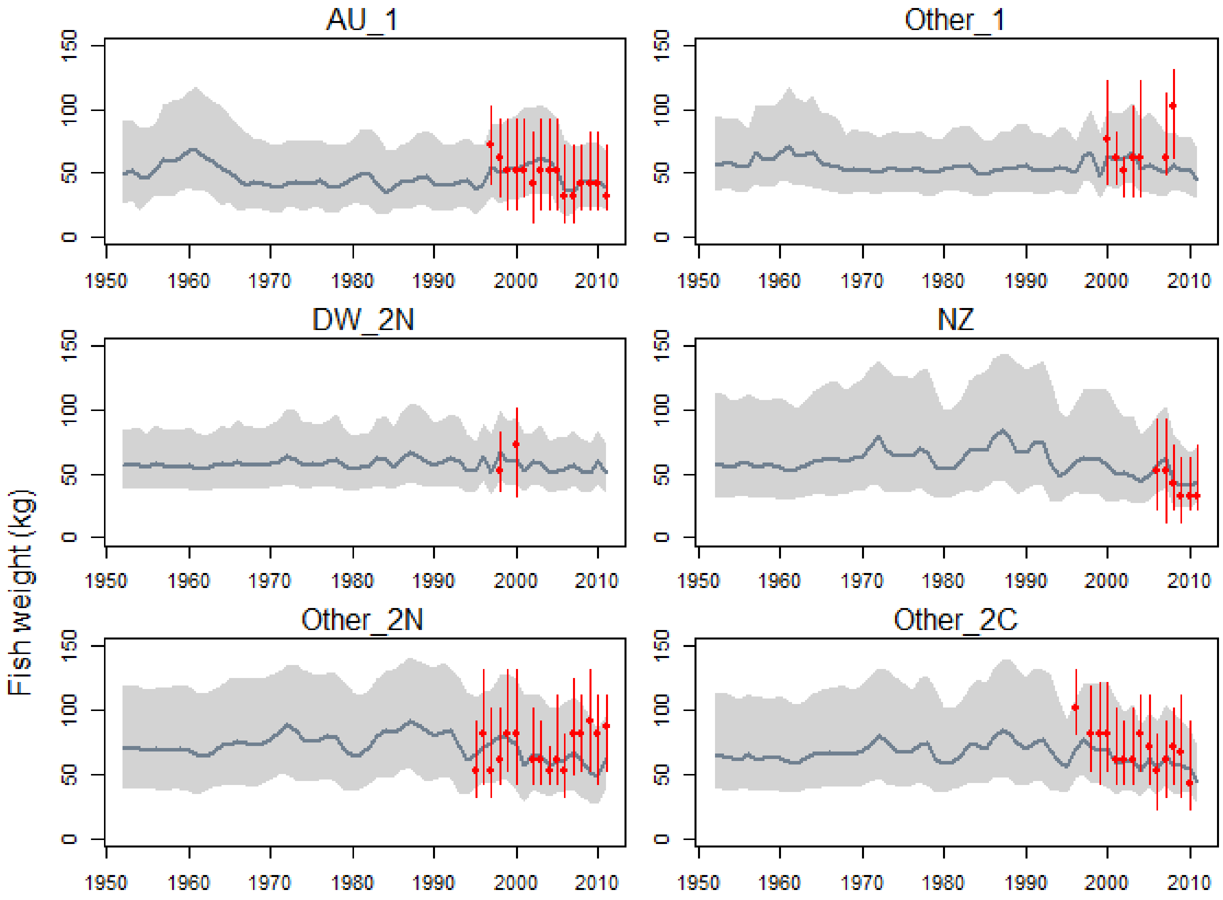


Figure 15: A comparison of the observed (points) and predicted (grey line) annual median weight (whole weight, kilogrammes) of swordfish by fishery for the main fisheries with weight data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Model estimates are from the Ref.case model.

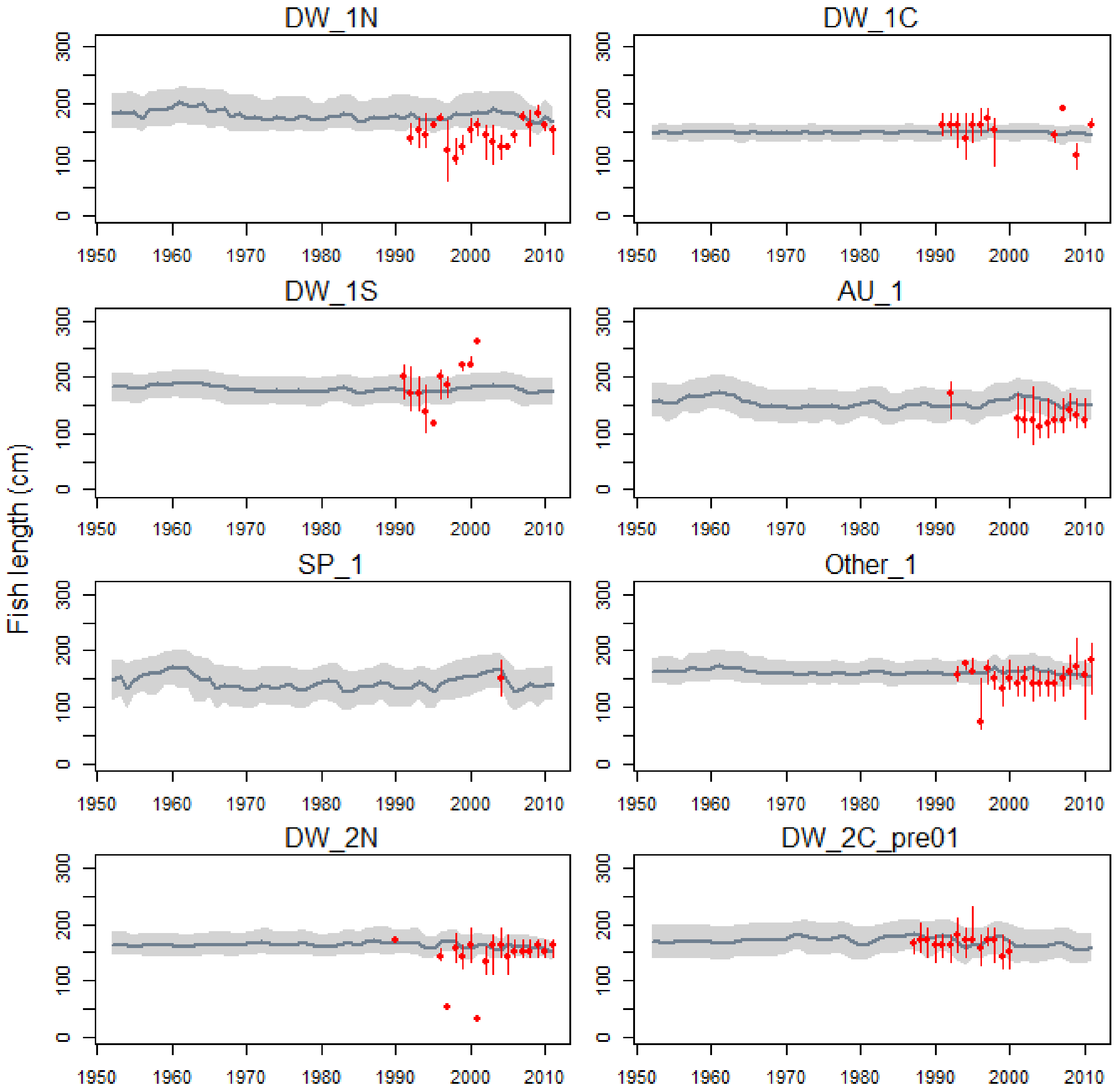


Figure 16: A comparison of the observed (points) and predicted (grey line) annual median length (LJFL, cm) of swordfish by fishery for the main fisheries with length data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Model estimates are from the Ref.case model.

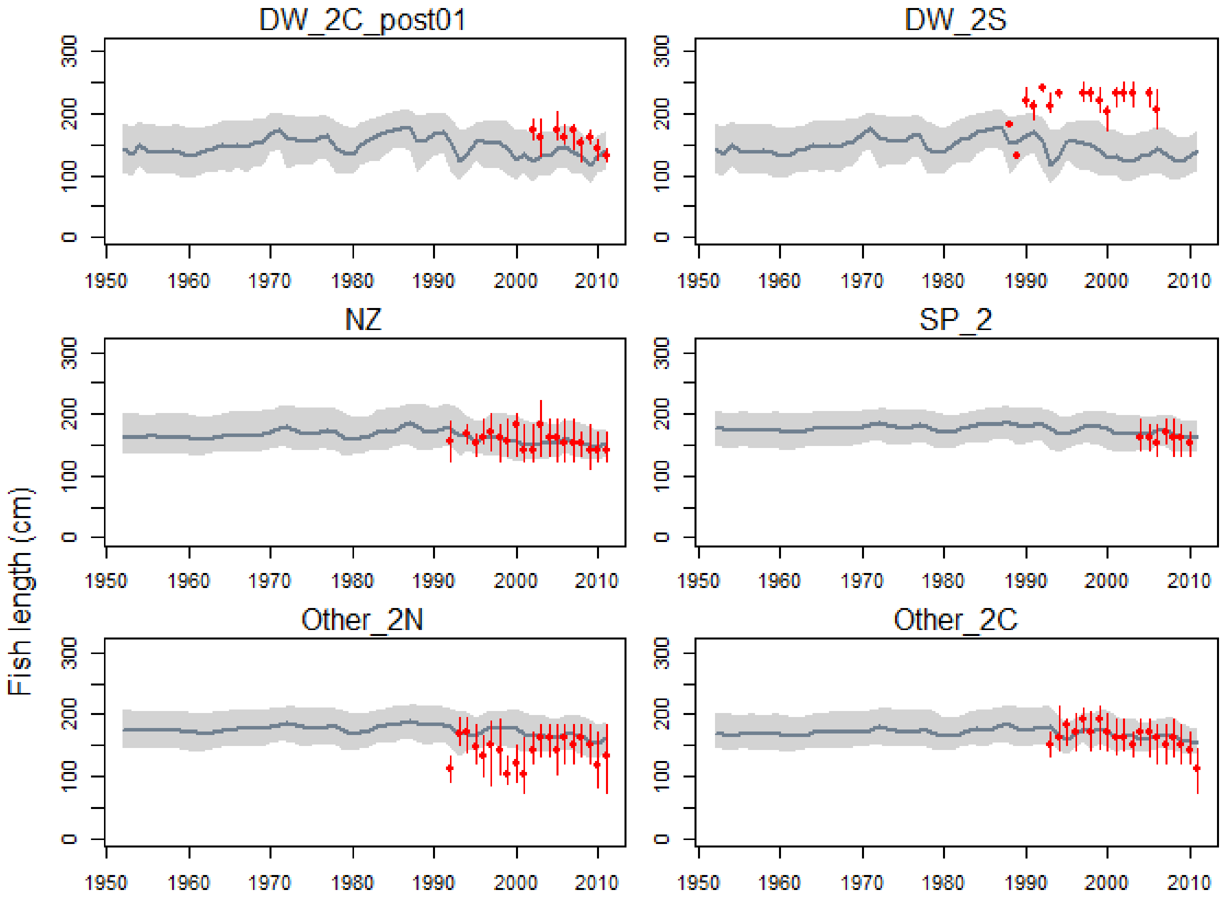


Figure 16 contd. A comparison of the observed (points) and predicted (grey line) annual median length (LJFL, cm) of swordfish by fishery for the main fisheries with length data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Model estimates are from the Ref.case model.

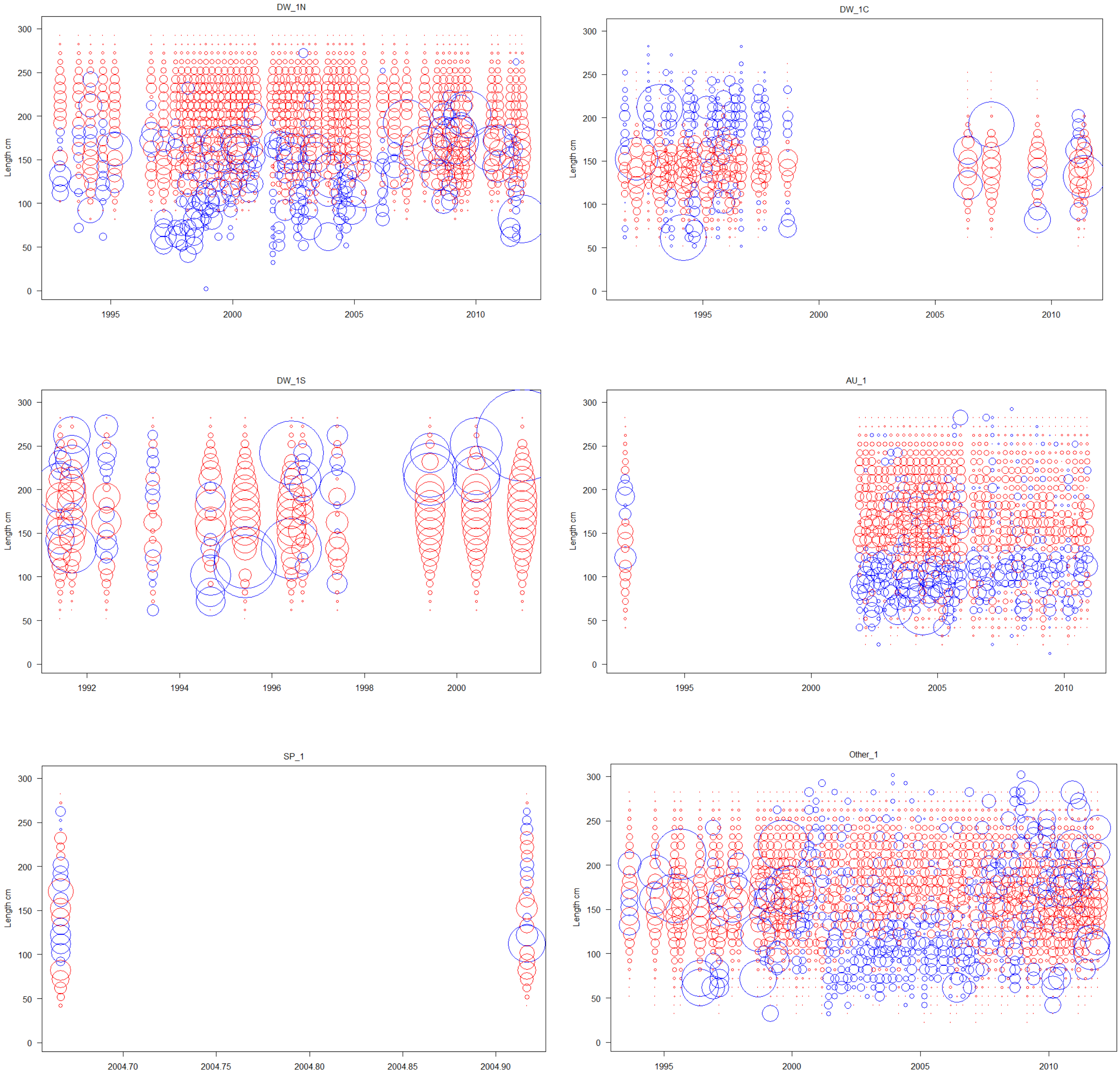


Figure 17: Residual plots of the fit to the length frequency data for the fisheries within the Ref.case model, Region 1. Positive residuals (more fish presented than predicted) are shown in blue and negative residuals in red. The diameter of circle is proportional to the square root of the residual.

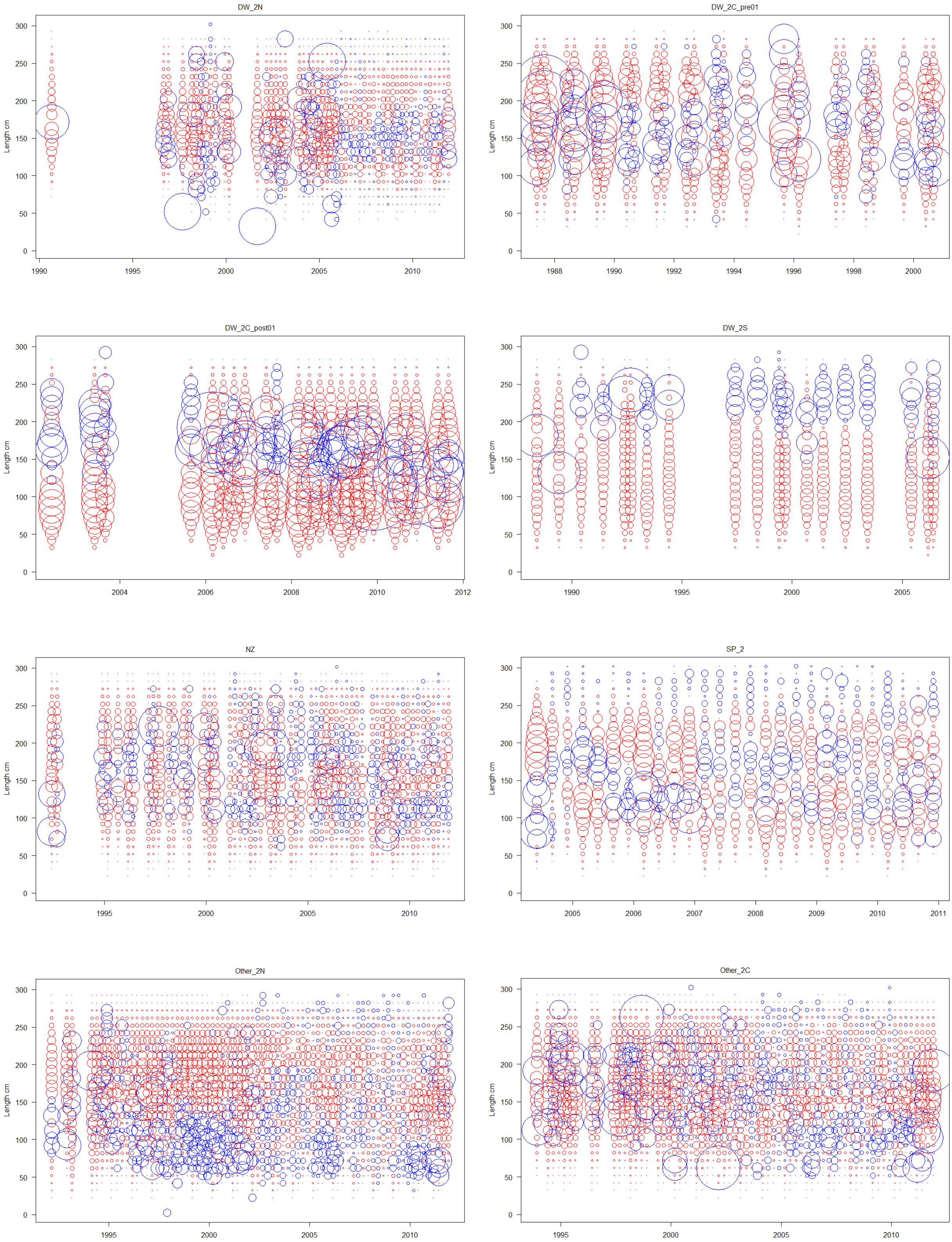


Figure 17 contd: Residual plots of the fit to the length frequency data for the fisheries within the Ref.case model, Region 2. Positive residuals (more fish presented than predicted) are shown in blue and negative residuals in red. The diameter of circle is proportional to the square root of the residual.

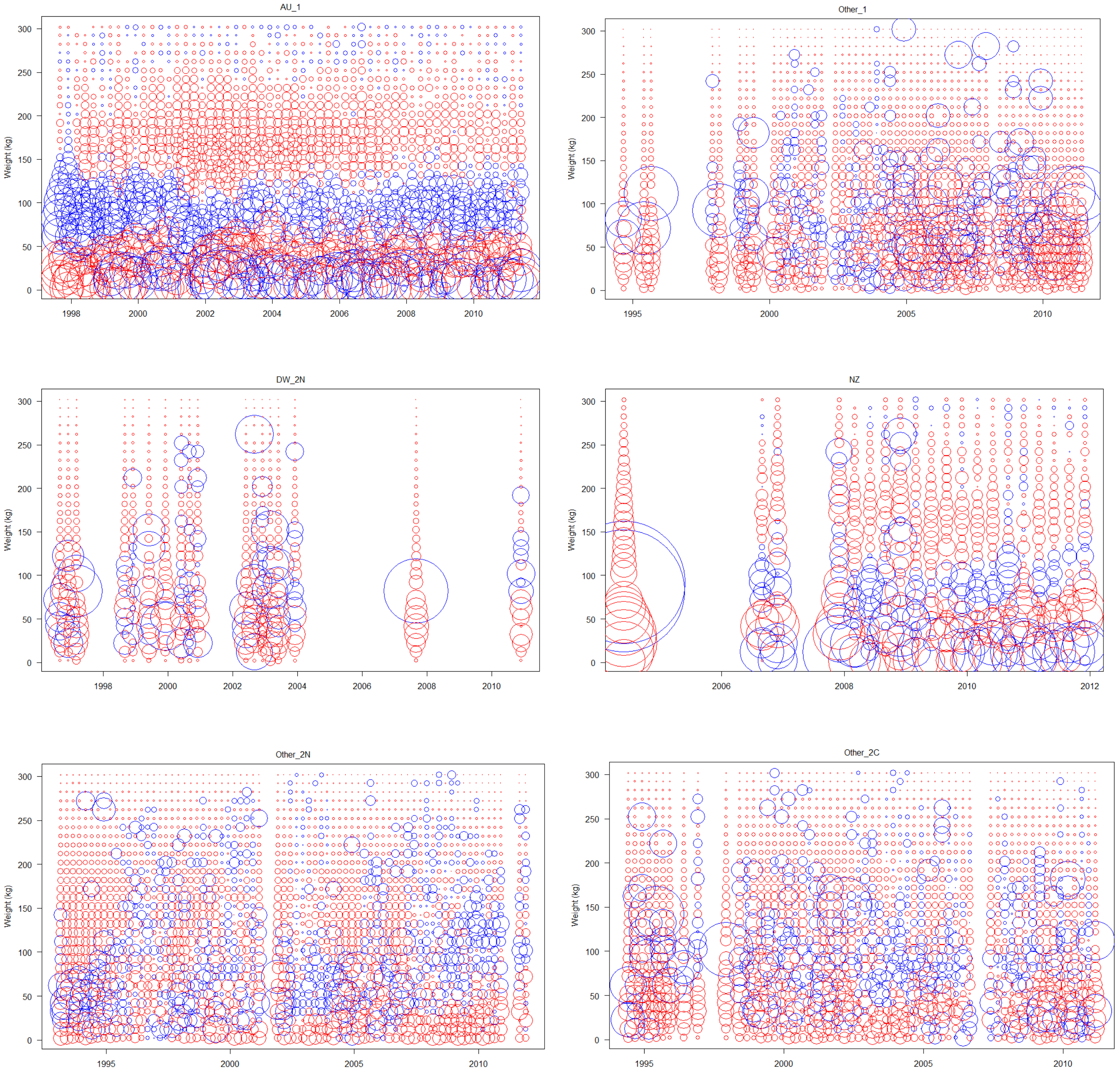


Figure 18: Residual plots of the fit to the weight frequency data for the fisheries within the Ref.case model. Positive residuals (more fish presented than predicted) are shown in blue and negative residuals in red. The diameter of circle is proportional to the square root of the residual.

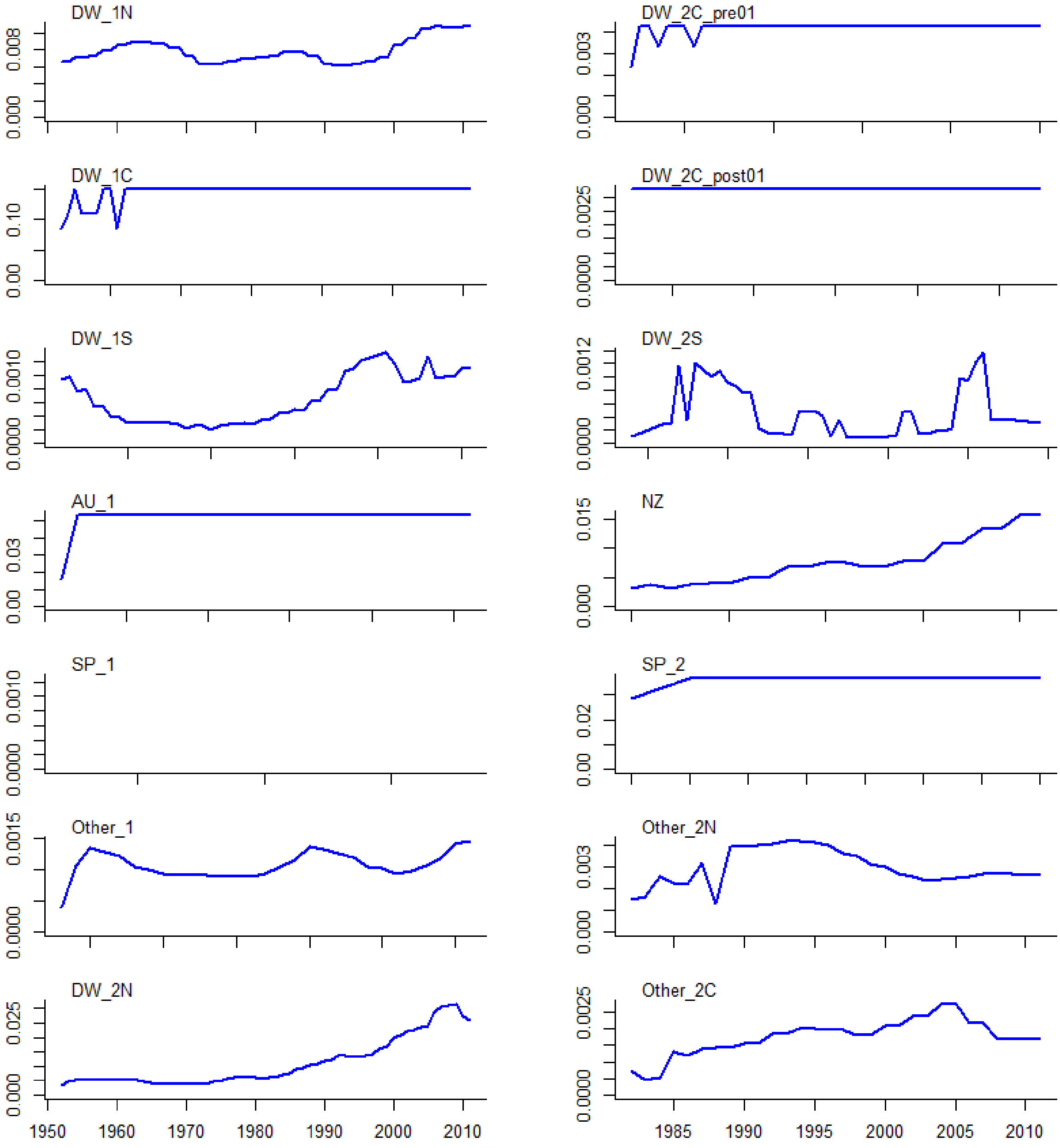


Figure 19: Average annual catchability time series for each fishery in the model region. Model estimates are from the Ref.case model.

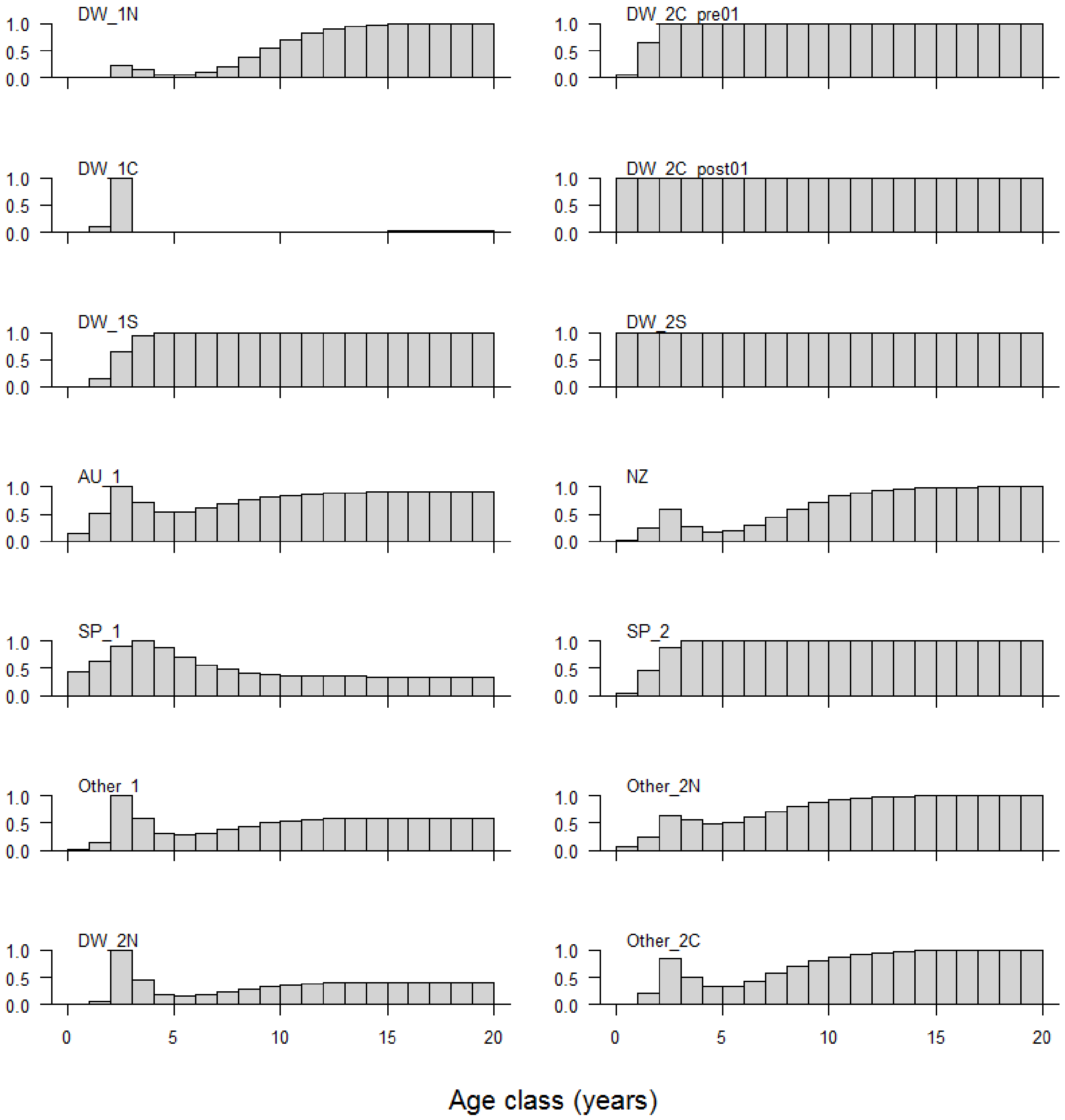


Figure 20: Selectivity coefficients for each fishery in the model region. Model estimates are from the Ref.case model.

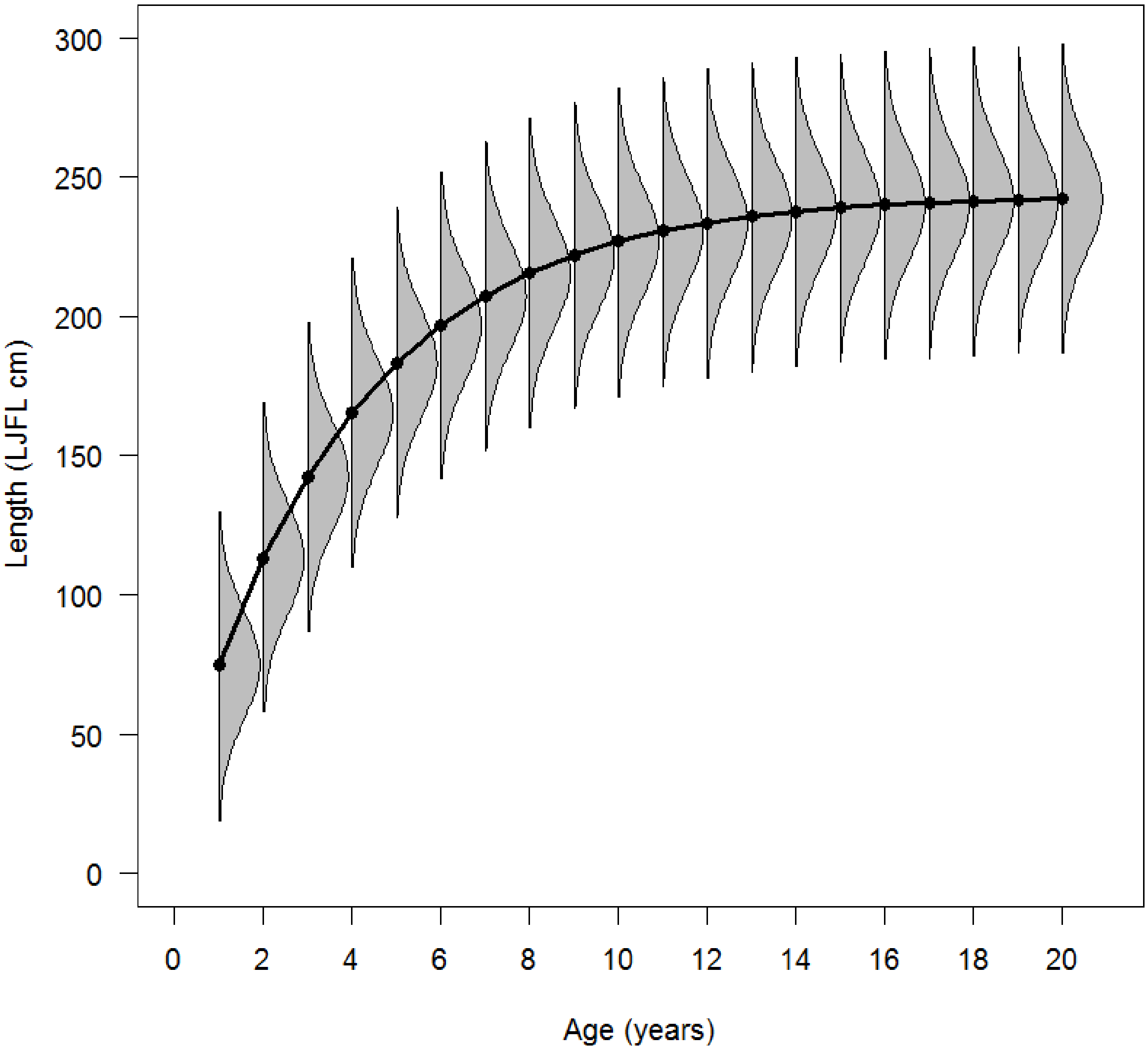


Figure 21: Growth parameters from the Ref.case swordfish model. The black line represents the fixed Hawai'ian growth function length (LJFL, cm) at age and the grey area represents the estimated distribution of length at age.

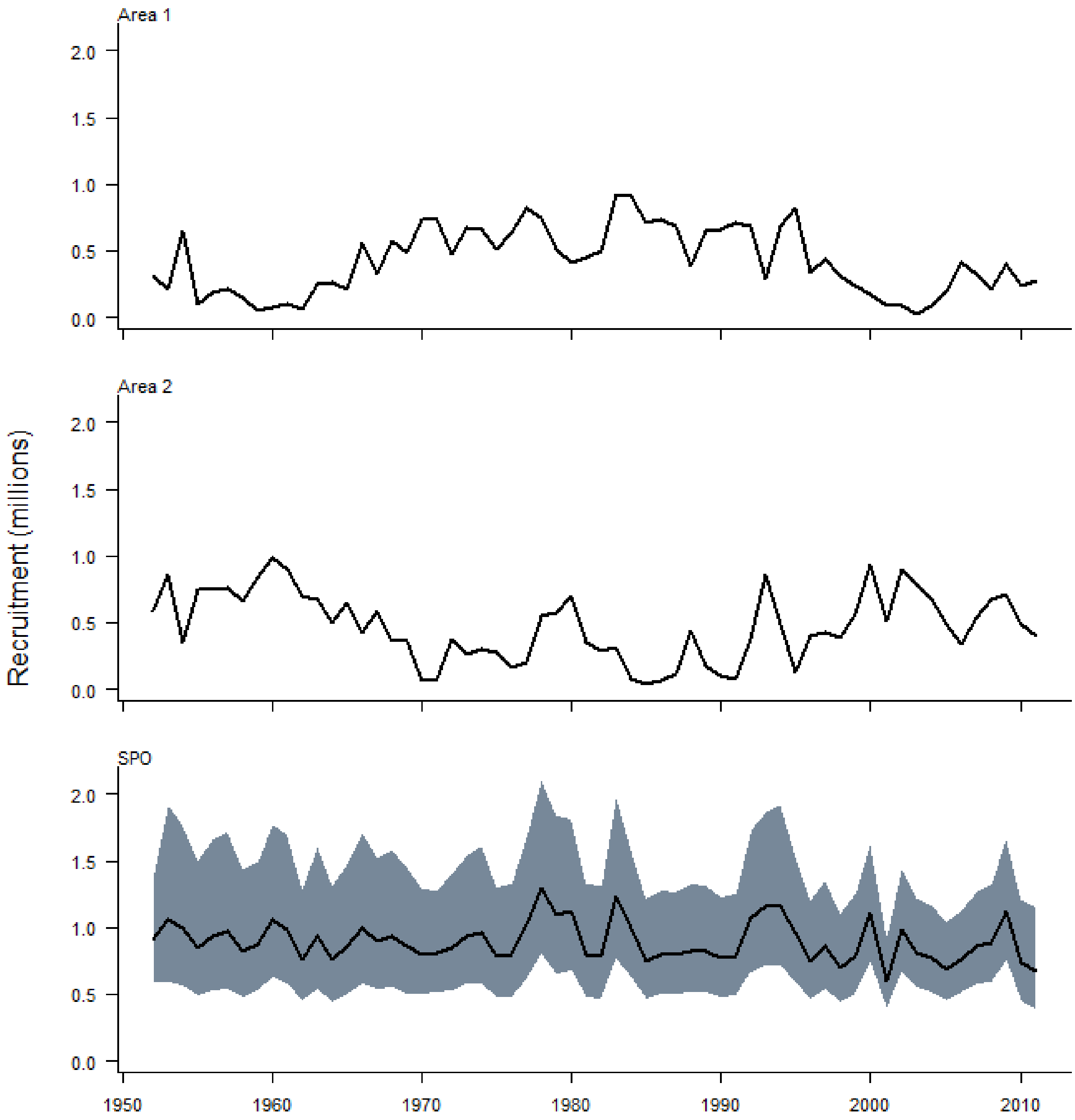
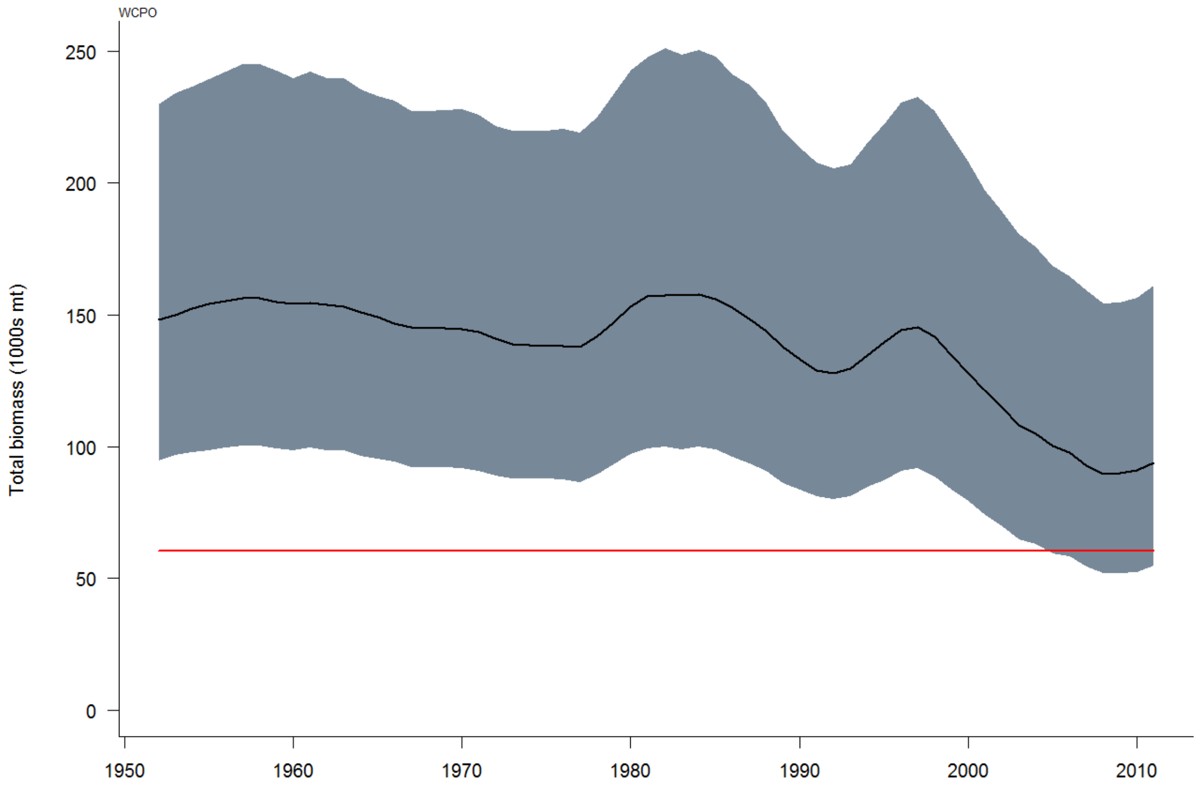


Figure 22: Annual recruitment estimates (number of fish) of swordfish in each of the model regions, and the combined model region. The shaded area in the combined model region figure indicates the approximate 95% confidence intervals. Model estimates are from the Ref.case model.



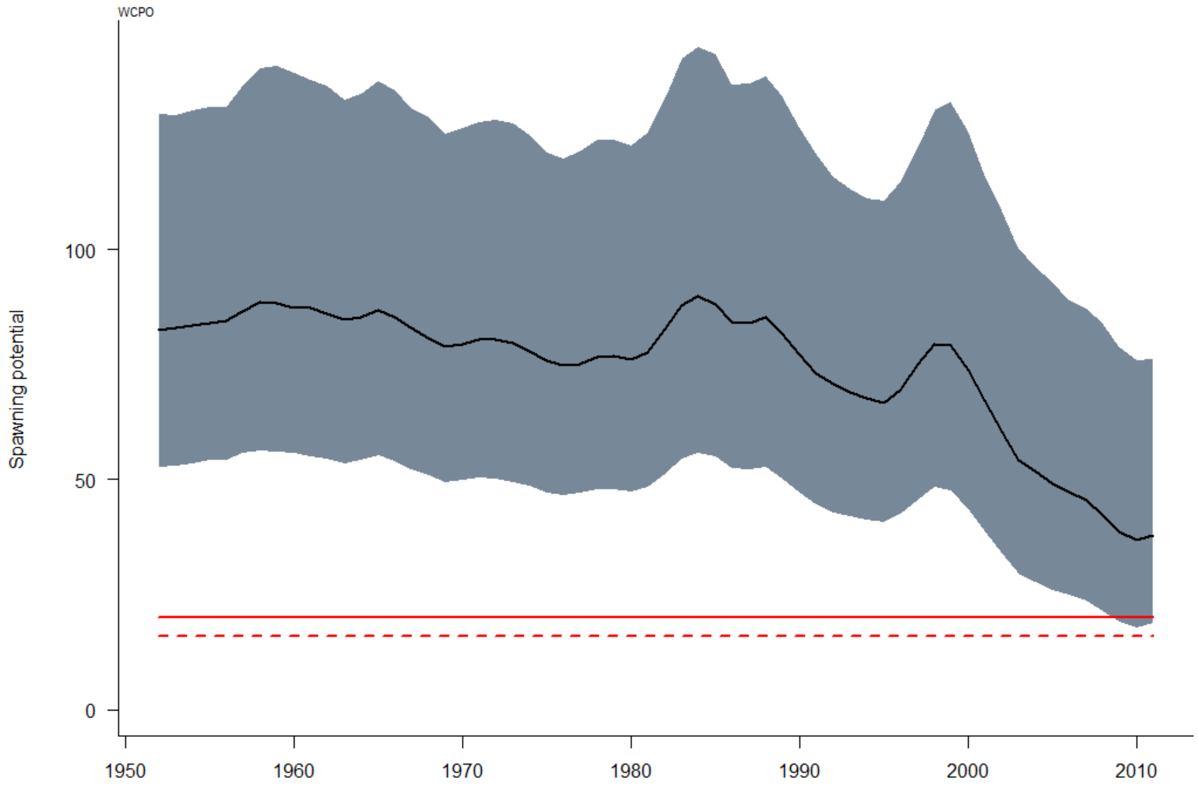


Figure 23: Annual Ref.case model estimates of total (top) and adult (bottom) swordfish biomass (metric tonnes) in the model region. The shaded area indicates the approximate 95% confidence intervals. The solid red line indicates the respective MSY levels, and the dashed red line indicates the 20% current period spawning biomass under zero fishing mortality ($SB_{currentF=0}$).

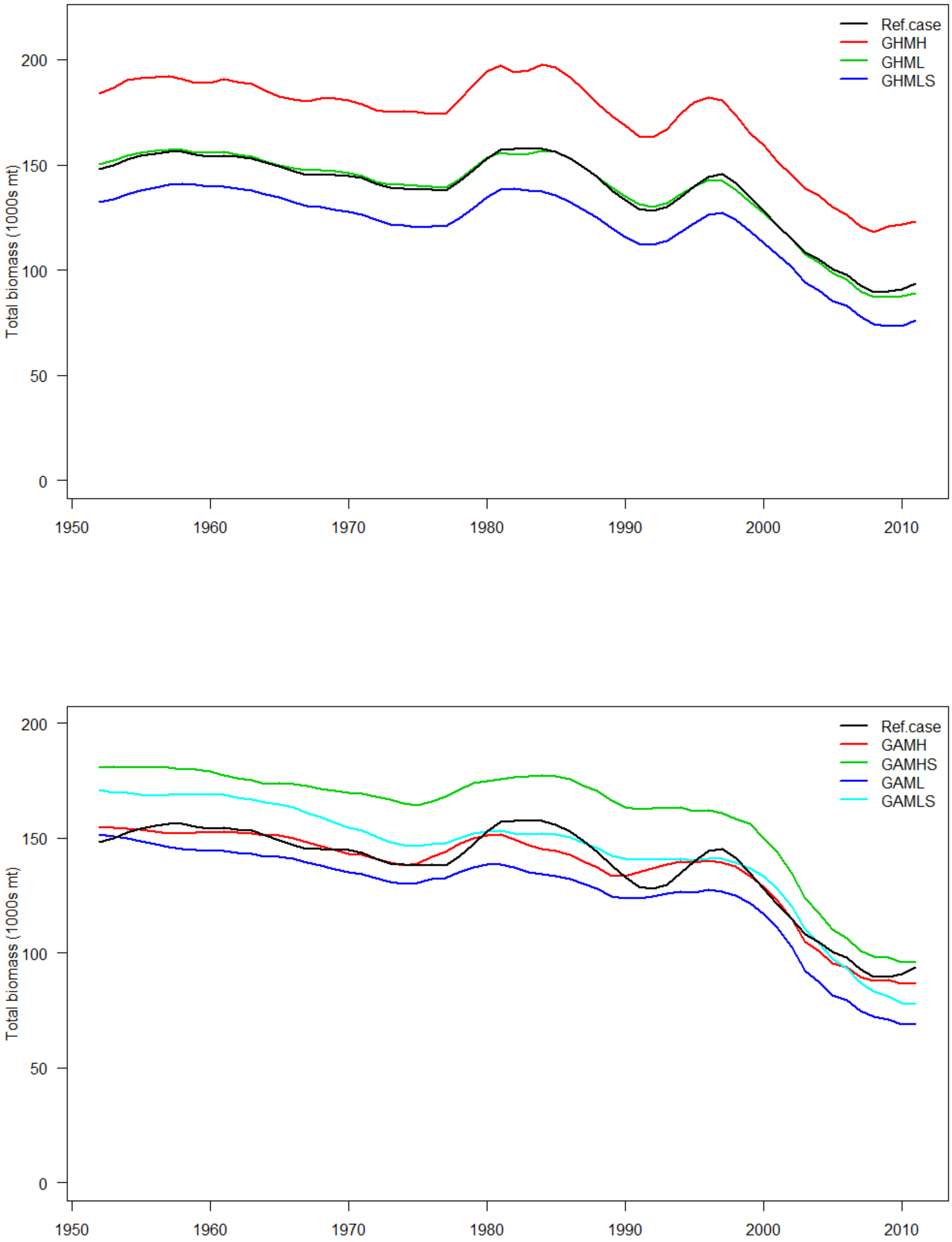
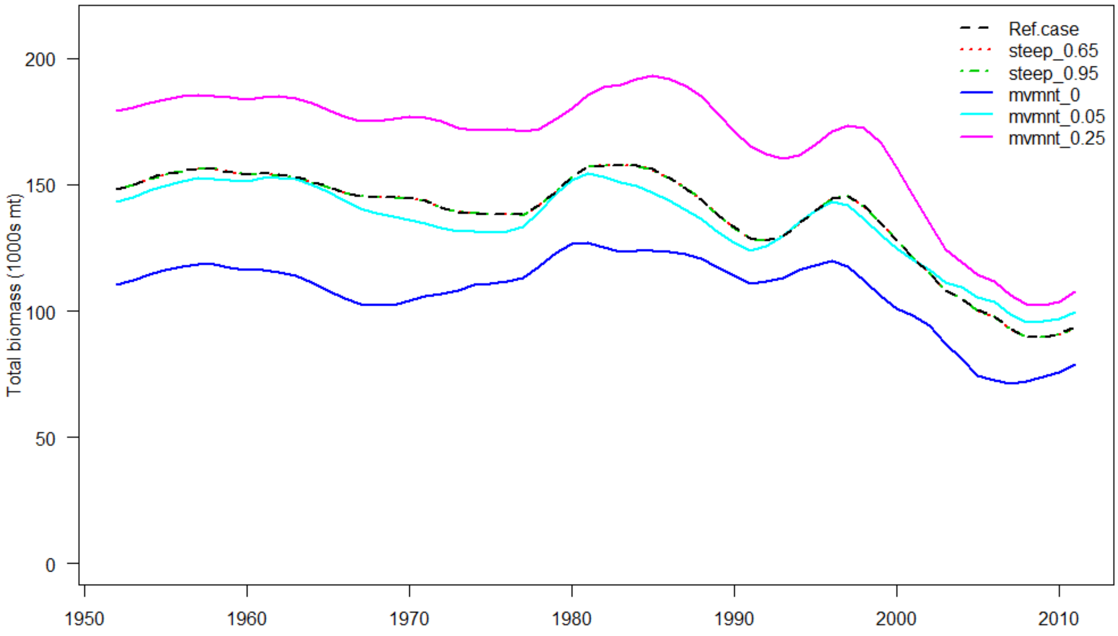


Figure 24a: Sensitivity of the Ref.case model to assumptions on mortality rate under that Hawai'ian schedule (top) and to the alternative Australian schedule and associated mortality settings (bottom).



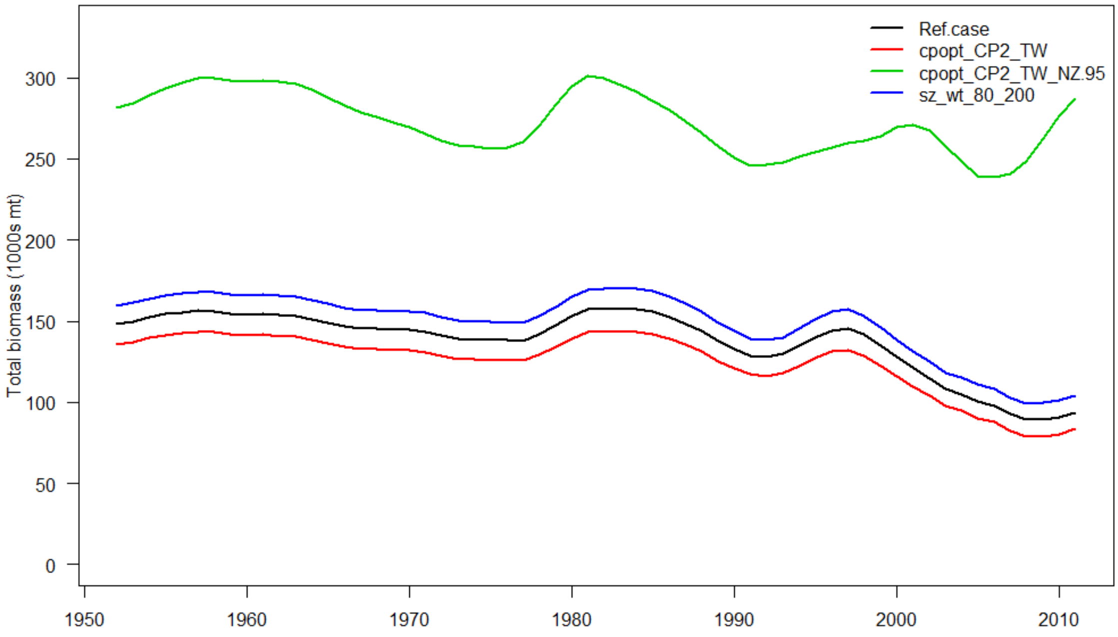


Figure 24b: Sensitivity of the Ref.case model to alternative stock-recruitment steepness parameter values and movement levels (top) and the use of alternative CPUE time series and weightings of the size data within the model fit (bottom).

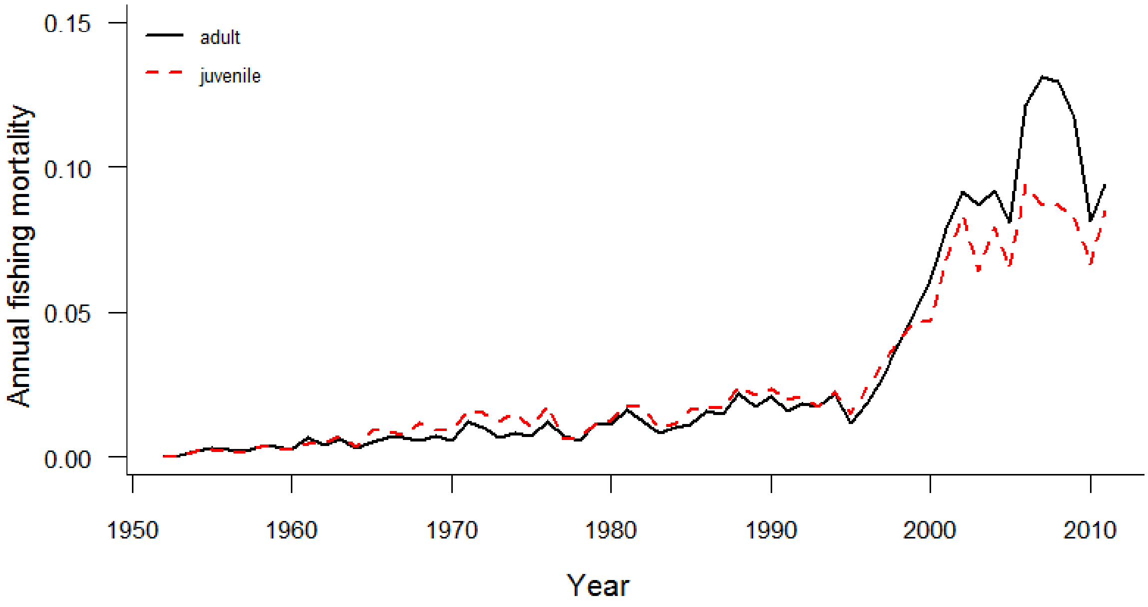


Figure 25a: Annual estimates fishing mortality for juvenile (red dashed line) and adult (black line) swordfish in the combined model region. Model estimates are from the Ref.case model.

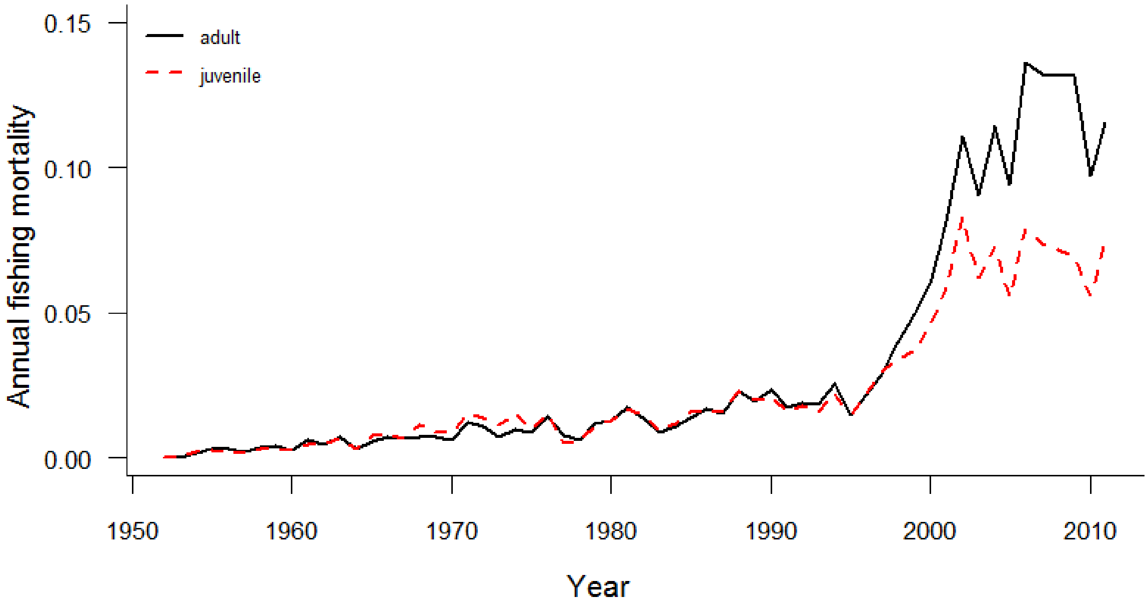


Figure 25b: Annual estimates fishing mortality for juvenile (red dashed line) and adult (black line) swordfish in the combined model region. Model estimates are from the GAMHS sensitivity model.

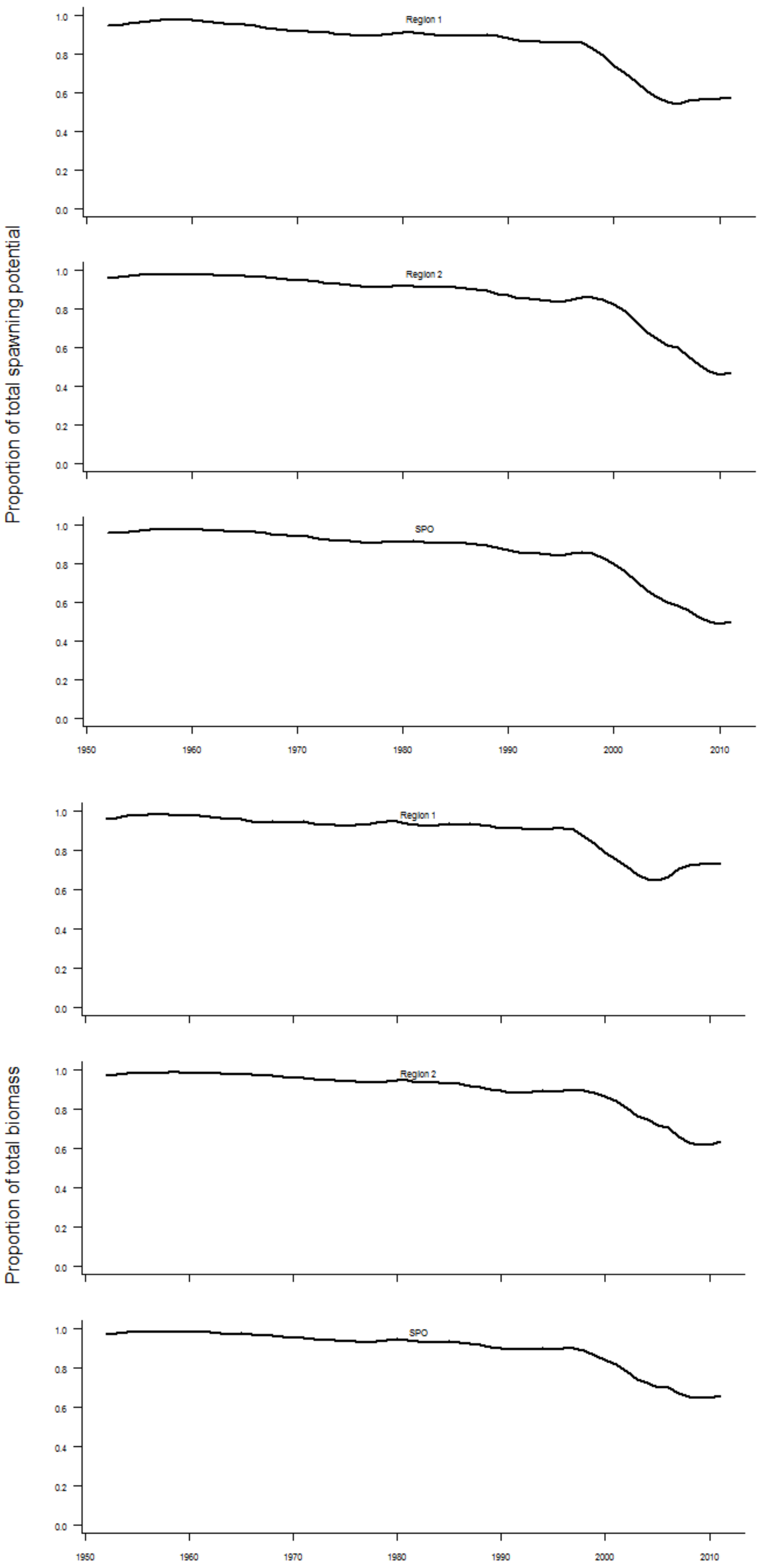


Figure 26: Annual estimates depletion expressed as the proportion remaining of the unfished spawning biomass (top three panels) and total biomass (bottom three panels) for each model region and for the south Pacific Ocean. Model estimates are from the Ref.case model.

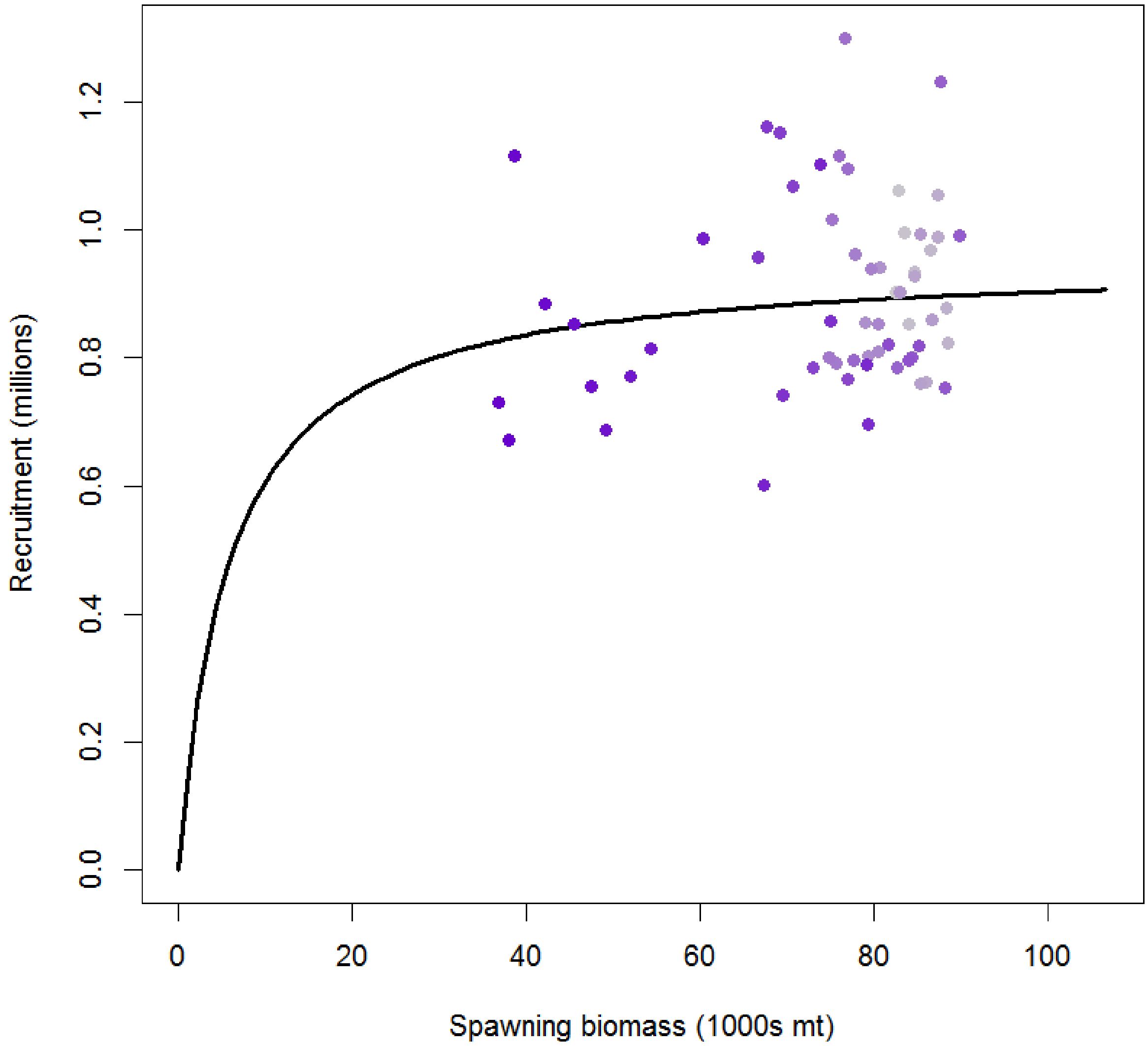


Figure 27: Spawning biomass – recruitment estimates for the Ref.case model and the fitted Beverton and Holt stock-recruitment relationship (SRR) for swordfish in the combined model region. Shading of the points from lighter to darker indicates estimates from the early to most recent years.

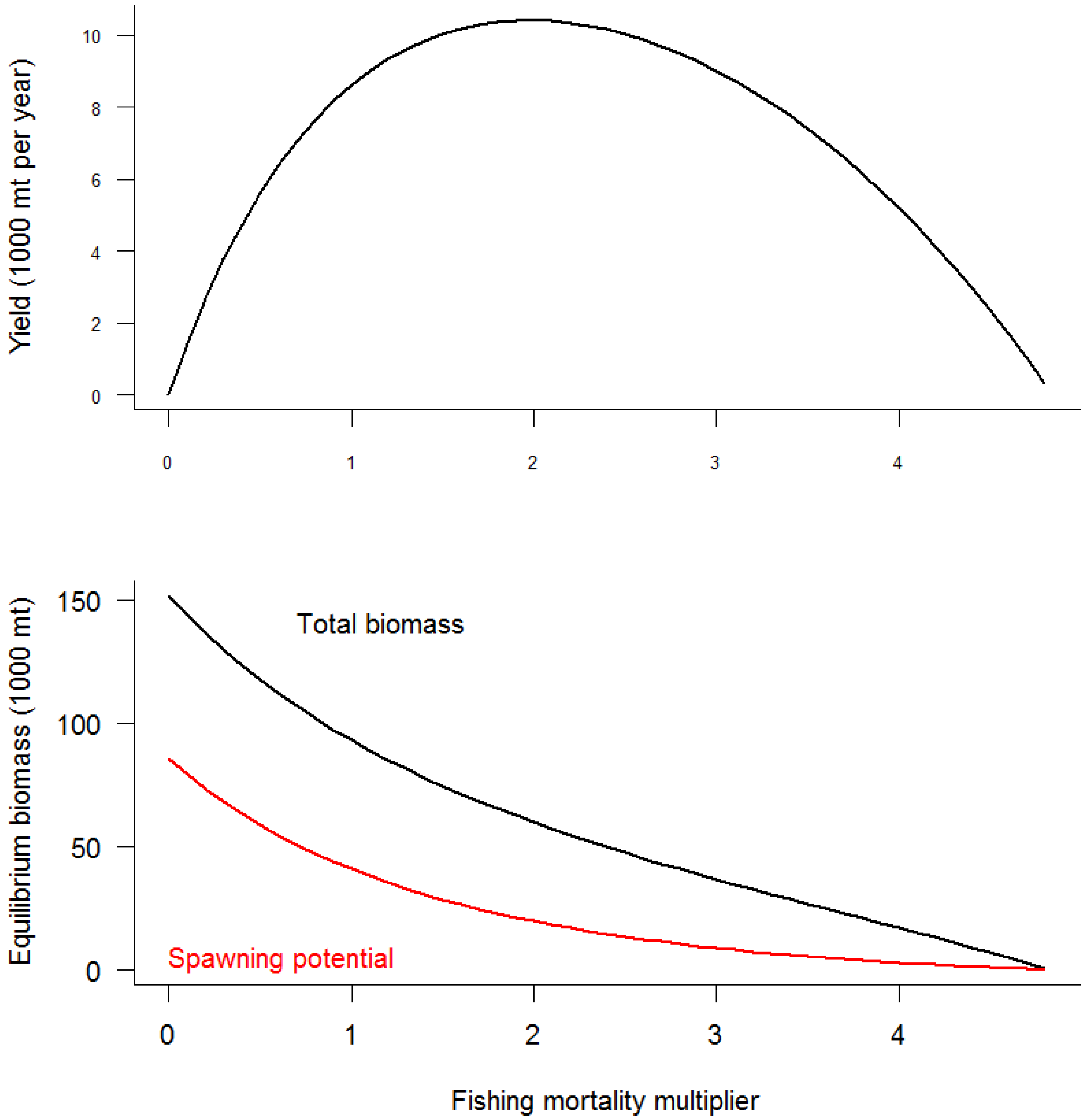


Figure 28: Equilibrium yield (metric tonnes) as a function of fishing mortality multiplier (*fmult*) for the Ref.case model. The shaded areas represent approximate 95% confidence intervals.

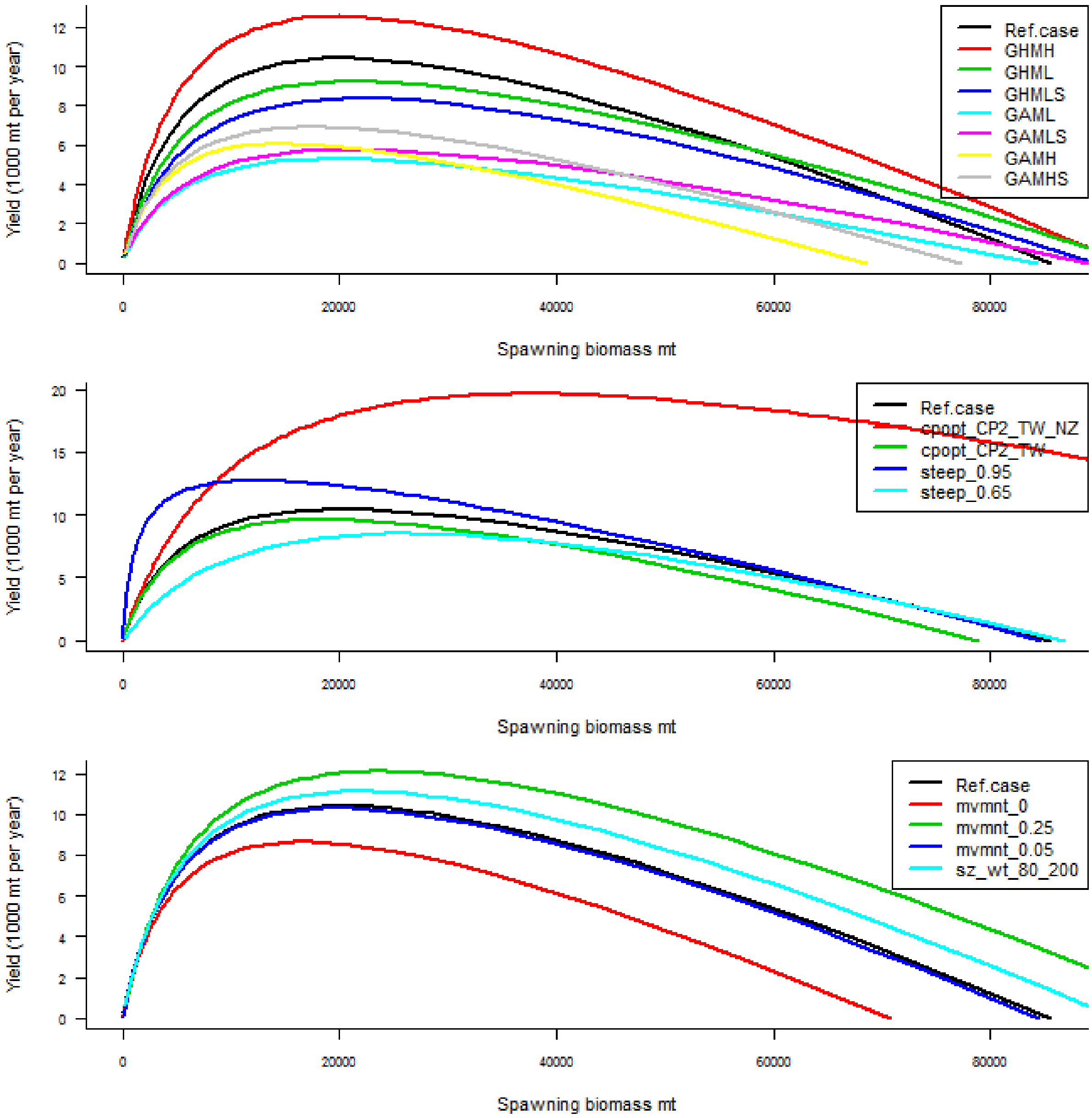


Figure 29: Estimated yields (mt) of swordfish at different levels of effort under the key model run assumptions. The Ref.case analysis is shown in black.

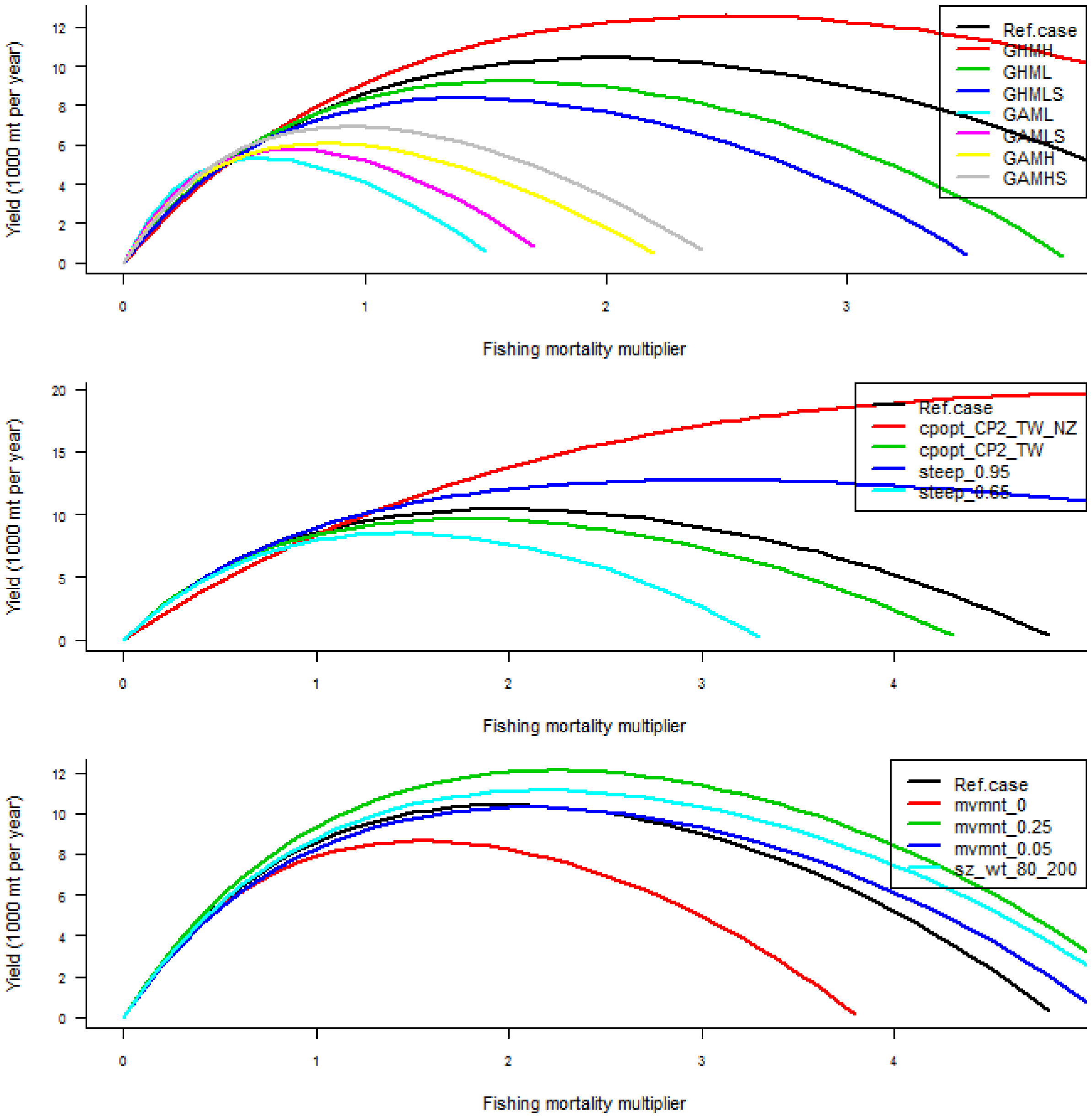


Figure 30: Estimated yields (mt) of swordfish at different levels of effort under the key model run assumptions. The Ref.case analysis is shown in black.

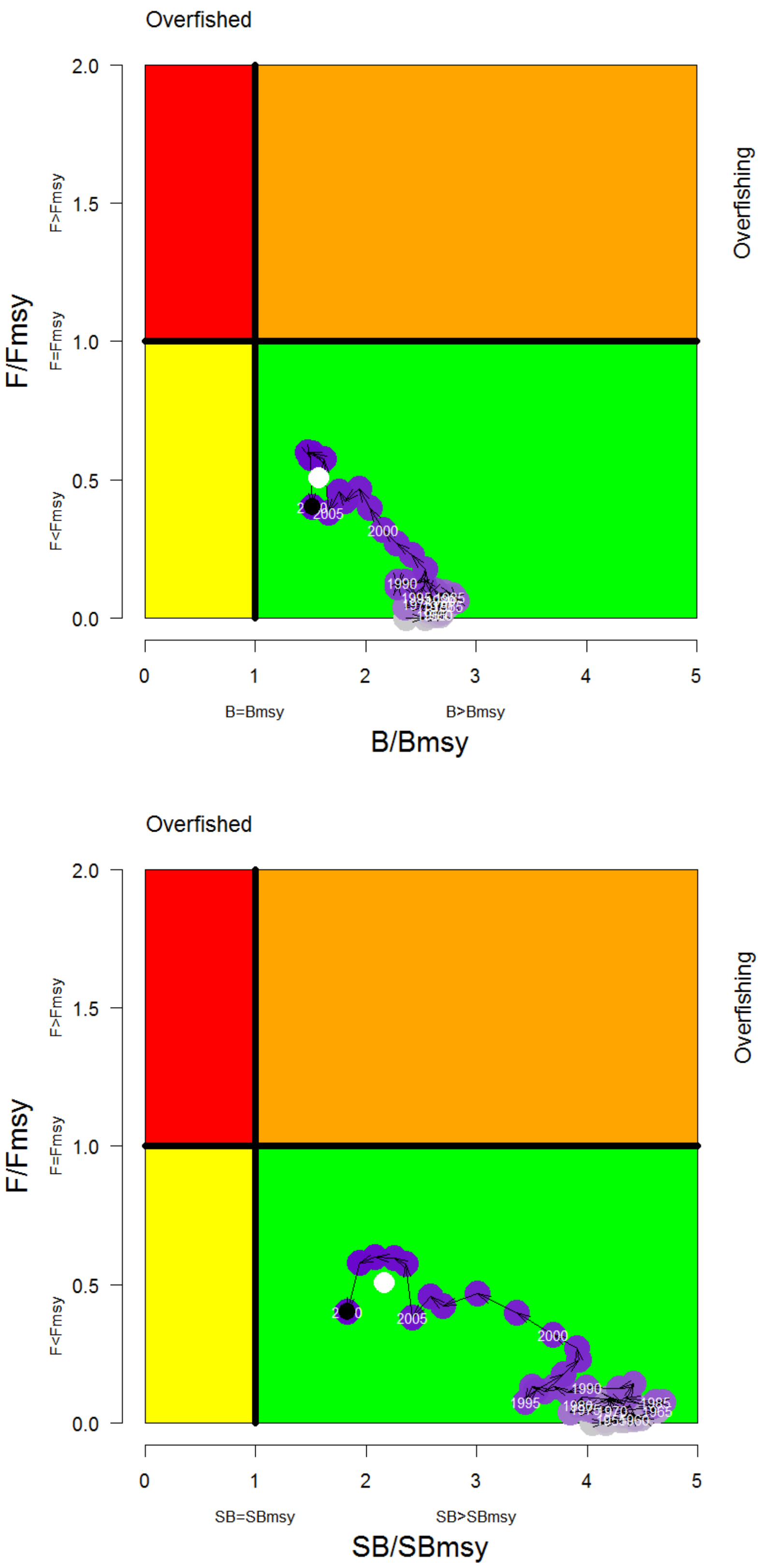


Figure 31: Temporal trend in annual stock status relative to B_{MSY} (x-axis) and F_{MSY} (y-axis) reference points (top), and SB_{MSY} (x-axis) and F_{MSY} (y-axis) (bottom), for the period 1952–2011 (Ref.case). The colour of the points is graduated from mauve (1952) to dark purple (2010) and the points are labelled at 5-year intervals. The white circle represents the average for the current period and the black circle the latest values.

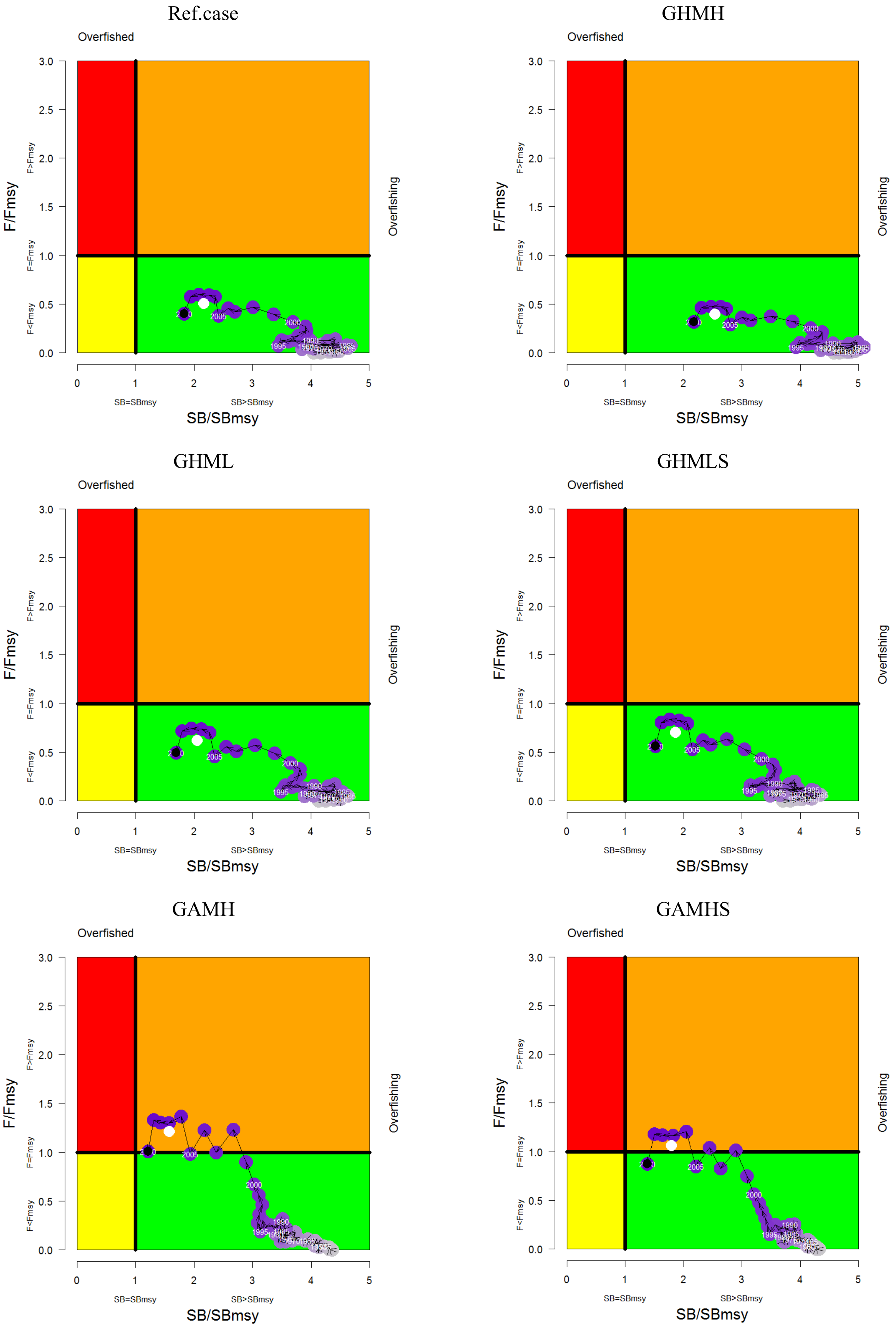
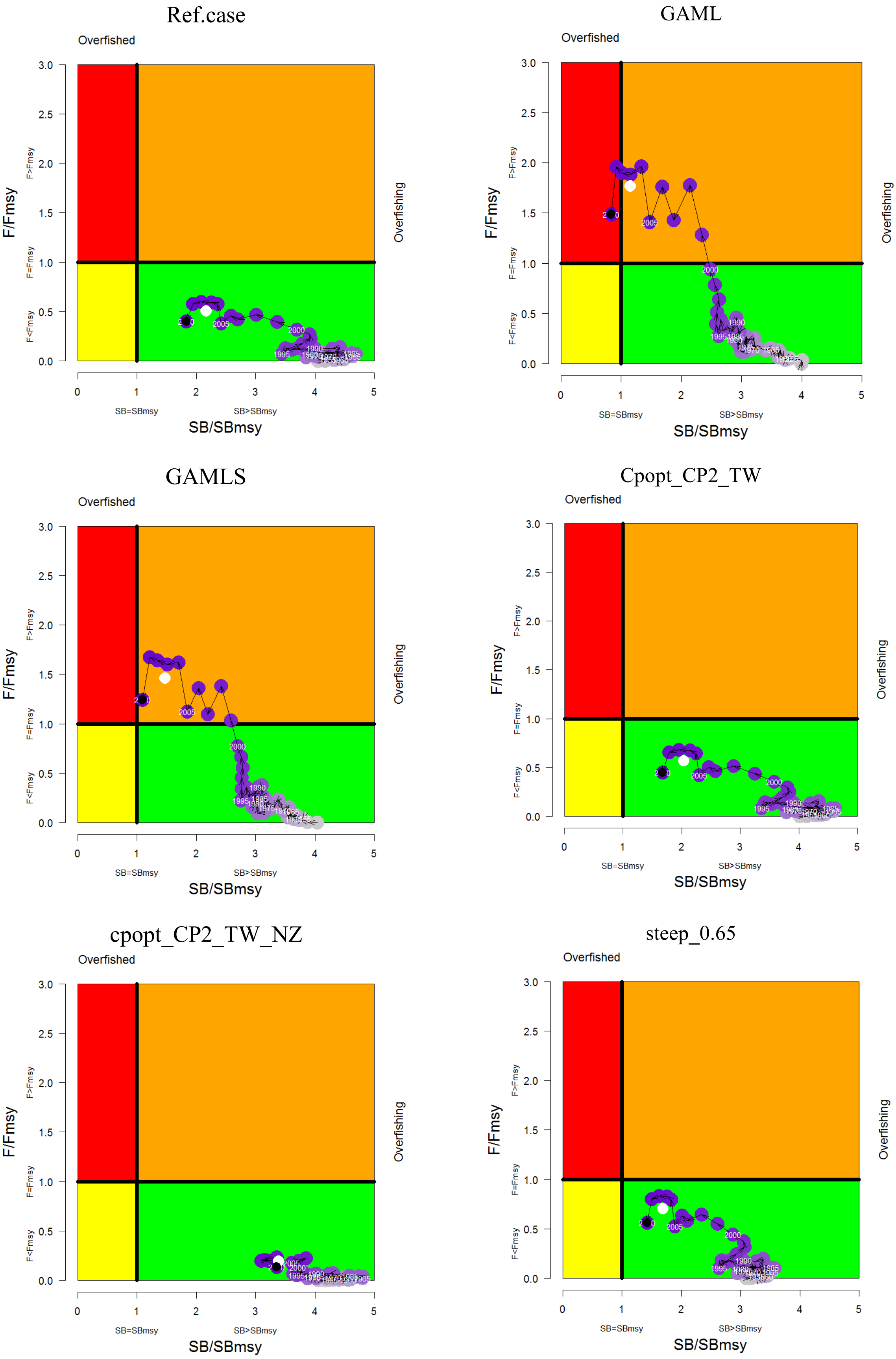


Figure 32: Temporal trend in annual stock status, relative to SB_{MSY} (x-axis) and F_{MSY} (y-axis) reference points for the Ref.case and key model runs.


Ref.case

GAML

GAMLS

Cpopt_CP2_TW

cpopt_CP2_TW_NZ

steep_0.65

Figure 32. 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.

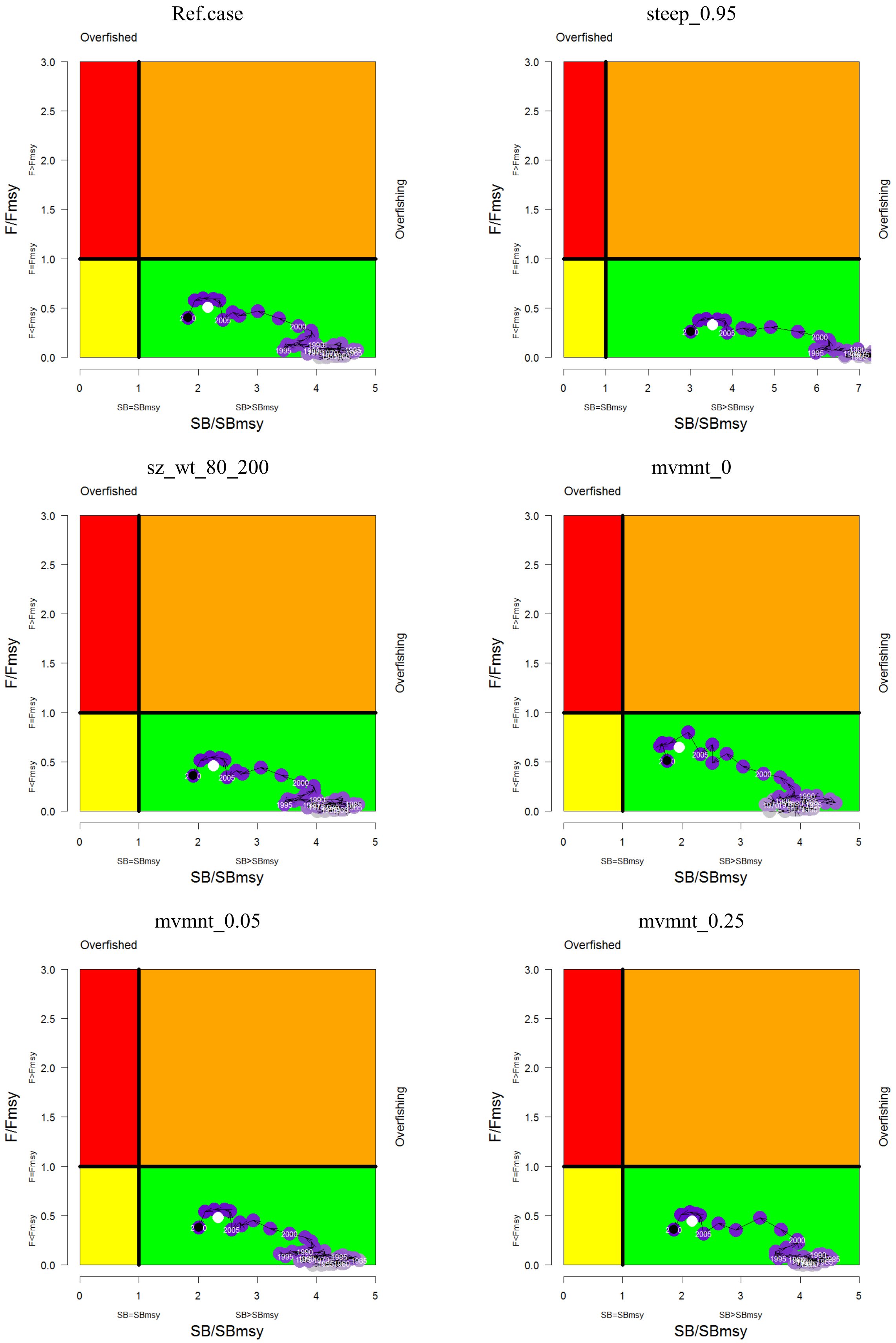


Figure 32. cont. Temporal trend in annual stock status, relative to SB_{MSY} (x-axis) and F_{MSY} (y-axis) reference points for the Ref.case and key model runs.

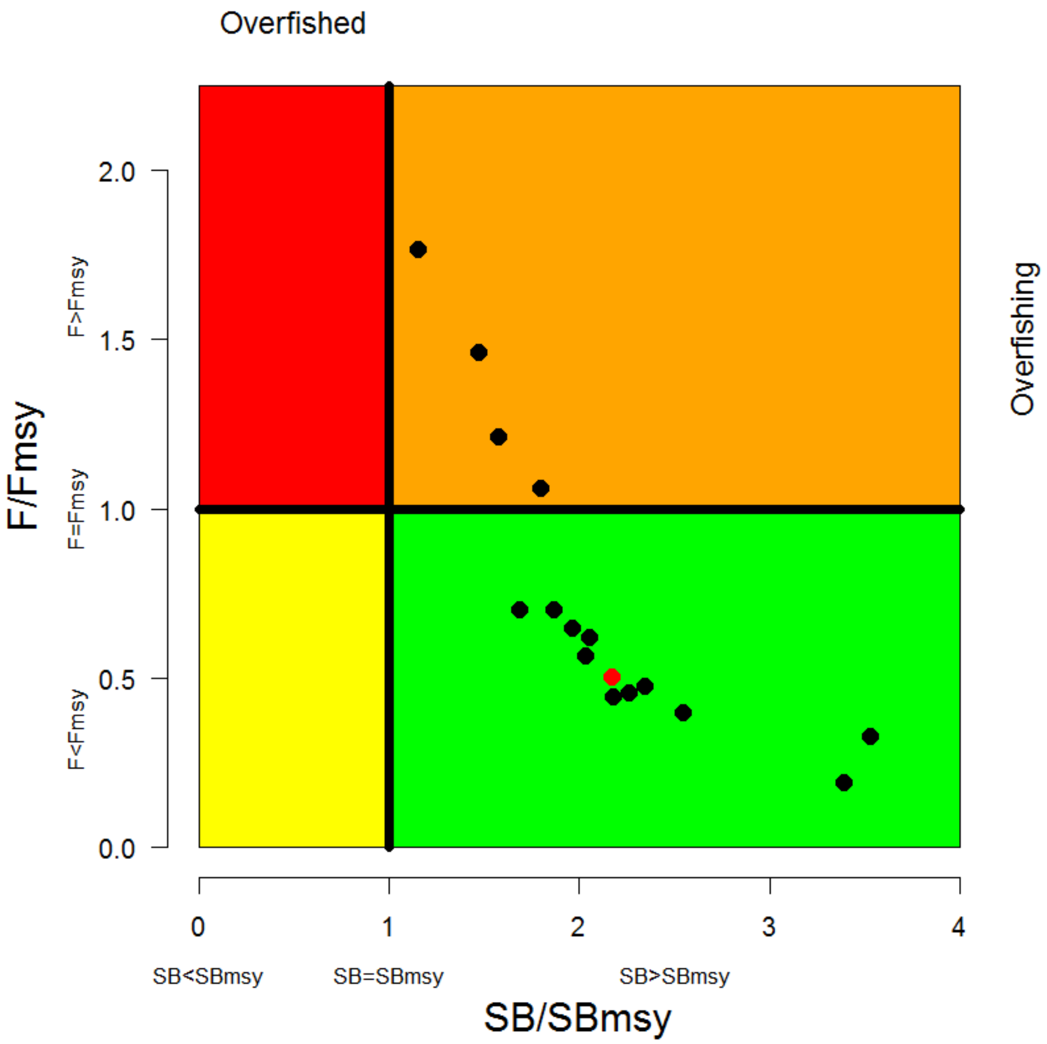


Figure 33: Summary of current stock status (based on 2010-11) for the key model runs. The red circle represents the Ref.case run.

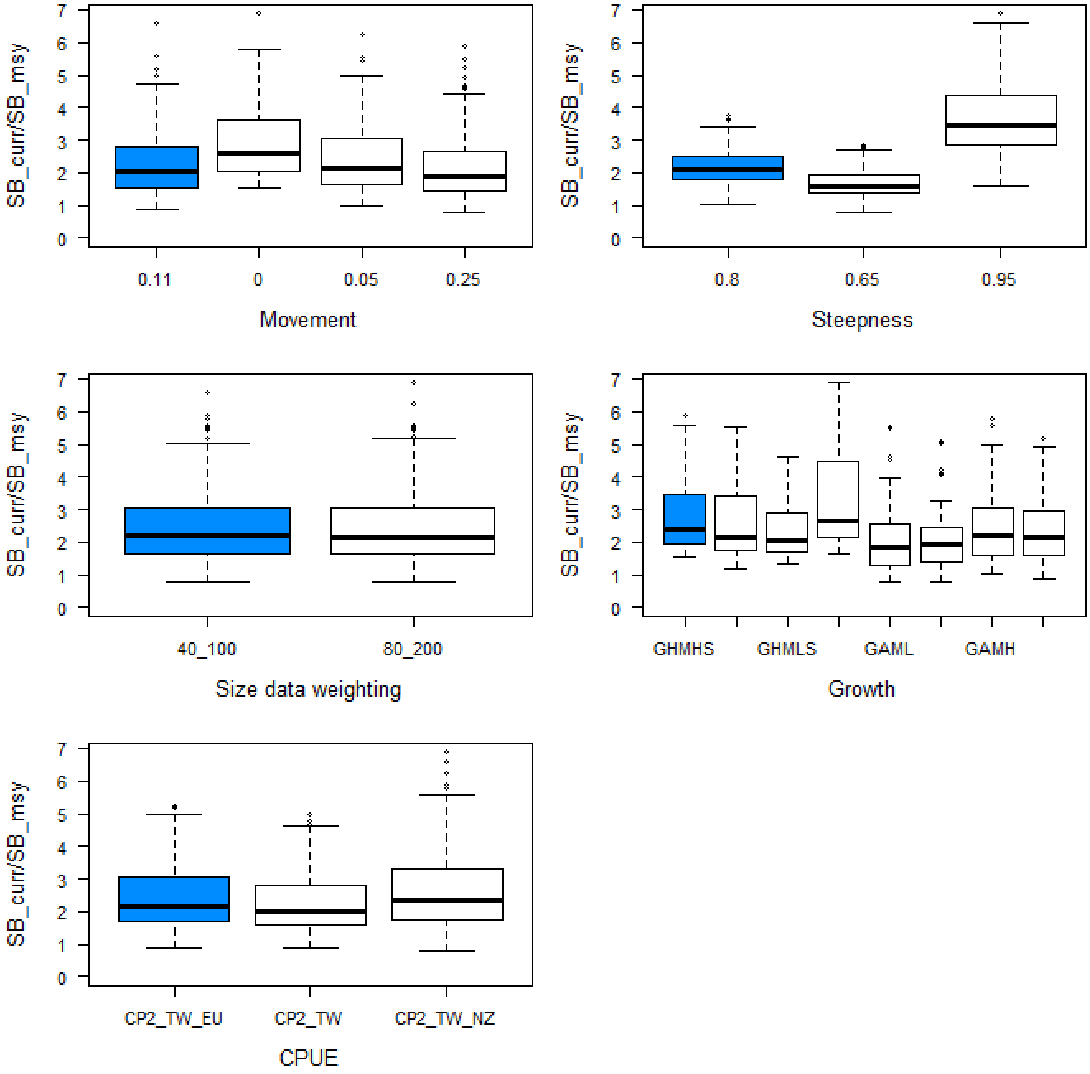


Figure 34: Stock status quantity SB_{curr}/SB_{MSY} with respect to the options investigated in each of the factors included in the uncertainty grid. The options associated with the Ref.case model are in blue.

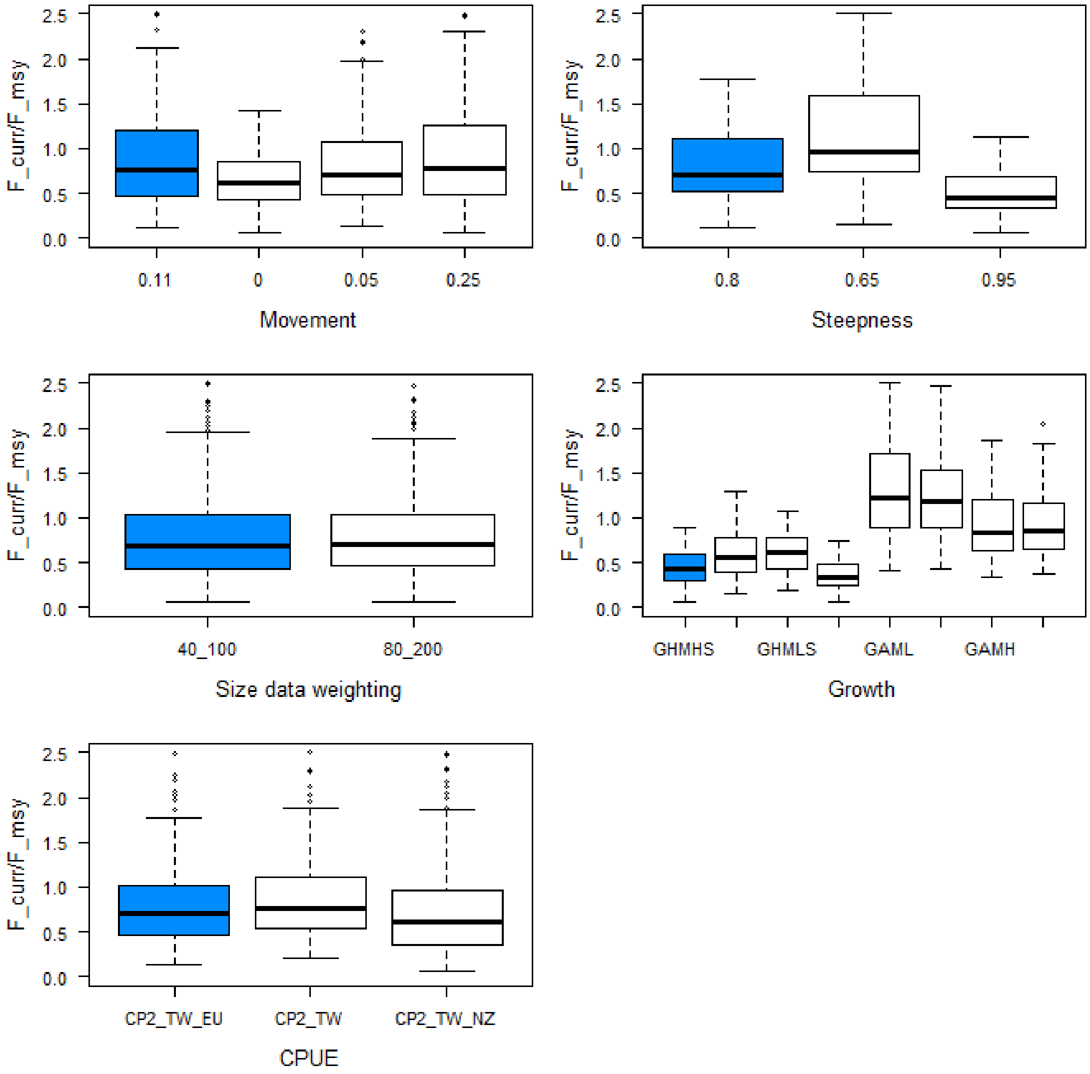


Figure 35: Stock status quantity F_{curr}/F_{MSY} with respect to the options investigated in each of the factors included in the uncertainty grid. The options associated with the Ref.case model are in blue.

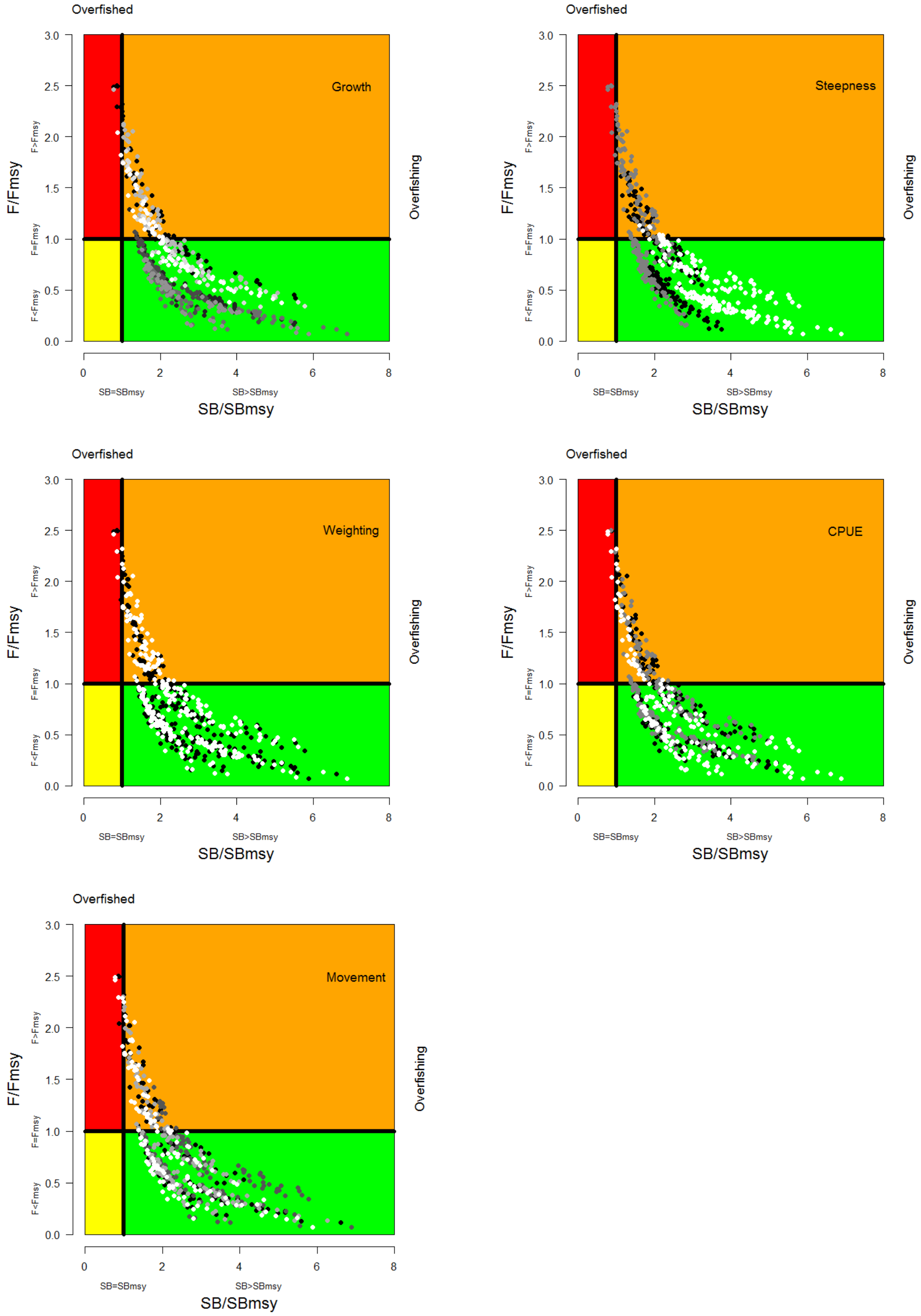


Figure 36: Plot of $SB_{current}/SB_{MSY}$ versus $F_{current}/F_{MSY}$ for the 561 model runs undertaken for the structural uncertainty analysis. The runs reflecting the Ref.case assumption are denoted with black circles while the runs with alternative assumptions, the symbols denote the alternatives in order shown in Table 7 from dark grey to white.