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A MULTIFAN-CL STOCK ASSESSMENT OF SOUTH-WEST PACIFIC SWORDFISH 1952-2007

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(REVISION 1)

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* This paper is a revision of the original submission 23 Aug 2008. The quantitative stock status summary remains unchanged, however, the presentation has been expanded and some errors corrected.

A MULTIFAN-CL Stock Assessment of South-West Pacific Swordfish 1952-2007

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Executive Summary

This paper describes a stock assessment for broadbill swordfish (*Xiphias gladius*) in the Southern region of the WCPFC convention area (0-50°S; 140°E -130°W) for the period 1952-2007 (including constant catch projections to 2017). The previous assessment (covering the period up to 2004) considered only the South-West Pacific (SWP) with an eastern bound of 175°W. The inclusion of the South-Central Pacific (SCP) in 2008 was in response to a request from the Commission to revisit WCPFC Conservation and Management Measure (CMM) 2006-3, which limits swordfish fishing effort in the southern WCPFC convention area, south of 20°S. There was a two-tiered approach to the assessment this year. The SWP was given the highest priority, because the evidence suggests that the population in this region may form a reasonably discrete sub-population, and there is compelling evidence to indicate that the population has declined due to fishing. A combined assessment on the SWP-SCP region was attempted as a lower priority because i) the available data in the SCP are poor, and ii) there is little evidence to suggest a strong link between the two populations (and it is plausible to assume that the SCP might be more closely linked with the north-central and/or south-east Pacific).

In the SWP, swordfish have been taken primarily as by-catch in the Japanese tuna longline fisheries since the 1950s, with reported annual catches fluctuating around 2000 *t* over the period 1970-1996. Japanese catches declined since the late 1990s, when the targeted Australian and New Zealand longline fisheries rapidly developed, with total annual catches averaging around 4000 *t* from 1997-2002. Catches have declined from 2002-2007, with total catches in 2006-7 now around the levels observed prior to 1997. Fiji, Papua New Guinea, Vanuatu and New Caledonia have reported the largest catches among the Pacific Island nations. Standardized catch rates declined substantially for all the major fleets during the period from around 1999-2004. Since 2004, there has been a substantial increase in the Australian and New Zealand catch rates, however, the increase is not as evident in the Japanese fleet. Mean size composition has declined in the well-sampled Australian fishery since the mid 1990s. Most of the swordfish catch in the SWP is taken in the region between 20-40°S.

The magnitude of the SCP swordfish catches has been comparable to the SWP since around 2000. Unlike the SWP, the majority of the swordfish in the SCP have been taken as by-catch in the equatorial tuna longline fisheries. Japanese SCP swordfish have been primarily a by-catch species since the early 1950s, and Korean catches began in the mid-1970s. Taiwanese fleets have taken substantial catches since ~2000. Beginning in 2004, the Spanish fleet has rapidly expanded, and this targeted fishery recorded the largest catches of all nations in the SWP-SCP in 2006. French Polynesia, Cook Islands and Vanuatu represent the majority of the SCP Pacific Island catches. There is no compelling evidence for changes in size composition in the SCP catches, however, size data are limited. Swordfish catch rates observed in the SCP suggest that swordfish abundance is stable or increasing in recent years. However, the operational level data available for conducting catch rate standardization analyses are limited, and some conflicting trends suggest that targeting changes are affecting CPUE trends for at least some of the fleets.

Major changes from the 2006 assessment include:

- Two-three years of additional data, which includes informative contrast in catch levels and CPUE in the SWP
- Simplification of the spatial structure within the SWP
- Quantification of swordfish mixing rates on the basis of recent Pop-up Satellite Archival Tags (PSAT) and conventional tagging studies
- Correction of catch data from NZ (~25% of landings were omitted in 2006)
- Additional size composition data (NZ port sampling from 2006-7, Spanish observer data from 2004)
- Exploration of alternative growth curves and maturity schedules, in light of evidence of methodological variability among laboratories
- Exploration of models that include the SCP population

This paper describes a quantitative stock assessment using MULTIFAN-CL software, while parallel comparative work was undertaken with CASAL (WCPFC-SC4-2008/SA-WP-7). The SWP assessment involved a substantial exploration of model uncertainty, with 768 model specifications proposed. All SWP models were age-structured (ages 0-19+), sex-aggregated, iterated on a quarterly timestep (1952-2007), spatially-disaggregated into two roughly equal longitudinal units, with 11 fisheries and 4 informative effort series. The varying model assumptions in the uncertainty 'grid' were explored in a balanced factorial design with:

- 2 stock recruitment curve steepness priors (0.65, 0.9)
- 2 diffusive mixing assumptions (0.05, 0.1 per quarter)
- 8 growth rate / maturity / mortality options
- 2 recruitment deviation options (SD of log-normal deviates = 0.1, 0.5)
- 2 sample size down-weighting options for catch-at-size likelihoods (1/5, 1/20)
- 3 relative weighting options for CPUE indices (fleets weighted differently)
- 2 selectivity constraint options

From this combination of models, 192 (defined as the Most Plausible Ensemble - MPE) were judged to be plausibly consistent with the data and prior expectations of the swordfish fisheries and biology.

The SWP stock status summary represents a synthesis of the results from all 192 models, from which we reach the following conclusions (estimates represent the median and range of the Maximum Posterior Density (MPD) estimates; it is shown in the text that the parameter estimation error for any individual model is much less than the uncertainty among models):

1) We consider relative biomass estimates for recent years to be the most reliable reference points, because they are the most closely linked to the highest quality data, and are reasonably robust to the alternative model assumptions explored. In 2006, Total Stock Biomass (TSB) was considered to be more reliable than Spawning Stock Biomass (SSB) reference points. However, given the recognition of additional uncertainty in growth rates in 2008, it is not clear that the TSB estimates are more robust than SSB. The Maximum Posterior Density results from the plausible model ensemble indicate:

- TSB(2007)/TSB(1997): median = 0.69, range = (0.55 – 0.83).
- SSB(2007)/SSB(1997) = 0.58 (0.42 – 0.71).

2) The ratio of TSB relative to the biomass estimated to have occurred in the absence of fishing (TSBNF) provides a measure of the fishery impact on the population that might be more meaningful than the biomass ratio at two points in time if the population has experienced non-stationary production dynamics (which many of these assessments suggest to some extent):

- TSB(2007) / TSBNF(2007) = 0.58 (0.45 – 0.79)
- SSB(2007) / SSBNF(2007) = 0.43 (0.31 – 0.63).

3) The data are not sufficient to estimate a stock recruitment relationship reliably, and most of the models explored suggest some form of long-term recruitment variability. This undermines the usefulness of the MSY-related reference points. However, in so far as these reference points have been calculated, all of the MPD estimates from the plausible model ensemble suggest that biomass (total and spawning) is above levels that would sustain MSY, and fishing mortality is below F(MSY).

- TSB(2007)/TSB(MSY) = 1.57 (1.22 – 2.06)
- SSB(2007)/SSB(MSY) = 1.98 (1.20 – 3.46)
- F(2007)/F(MSY) = 0.44 (0.18 – 0.67)

4) The stock projections (assuming deterministic future recruitment from the stock recruitment relationship, and constant catches at 2007 levels), suggest that rebuilding would be likely:

- TSB(2012) / TSB(2007) = 1.19 (1.03 – 1.54)
- SSB(2012) / SSB(2007) = 1.21 (0.91 – 2.07)
- TSB(2017) / TSB(2007) = 1.24 (1.05 – 1.64)

- SSB(2017) / SSB(2007) = 1.41 (0.94 – 2.30)
- TSB(2012) / TSB(MSY) = 1.89 (1.38 – 2.94)
- TSB(2017) / TSB(MSY) = 1.97 (1.43 – 2.99)

Overall, the 2008 SWP assessment yields results that are consistent with the results presented in the 2006 assessment. The uncertainty appears to be substantially reduced in 2008, in that the models are much more consistent in their stock status inferences and none of the models yielded results that were near the extremes that were judged to be plausible in 2006. There are two main factors likely contributing to this perception of reduced uncertainty. First, the 'one-way-trip' nature of the fishery has been interrupted, with recent declines in catch and effort resulting in stock rebuilding, such that the exploitation history now has informative contrast that improves the estimation of productivity. Second, the simplified spatial structure in the 2008 model reduces the flexibility for the model to create spatial refuges and 'cryptic biomass' reserves.

An attempted assessment on the combined SW and SC Pacific was undertaken, with a similar approach to the SWP, and an uncertainty grid of 144 models fit. However, none of the results were satisfying, for reasons that were anticipated during the 2006 assessment and discussed at the swordfish assessment workshop in April 2008 (WCPFC-SC4-2008/SA-IP-1). The nominal and standardized CPUE series from all the major fishing fleets in the SCP are either stable or show a continuous upward trend for the last several years (up to 20 or more) that has been sustained despite a rapid increase in catches. There is also a paucity of size composition data in the SCP. Thus there are no informative signals in either the CPUE or size composition data with which to quantify the fishery impact on the SCP stock. If it is assumed that the SCP CPUE indices provide reasonable relative abundance indices, then all of the models estimate a trend in increasing recruitment for most of the duration of the SCP fishery. In many cases, the models estimate very low stock recruitment curve steepness (i.e. a linear relationship between spawning biomass and abundance), with the paradoxical suggestion that both biomass and recruitment are increasing over time, despite very low MSY and chronic overfishing relative to MSY. In other cases, the models suggest that recruitment is stable or increasing, biomass is very high and the fishery catch is a negligible proportion of the stock. It is possible that the SCP is experiencing a long-term change in recruitment productivity, in which case none of these models are very helpful for predicting what will happen in the future. If this is true, it also suggests that the SCP swordfish population is not rapidly mixing with the SWP population, as the general CPUE trends in the two areas are in opposite directions despite a similar magnitude of catch removals. However, another plausible explanation for the increasing CPUE trends is a change in gear deployment practices in the SCP. One can never be confident that commercial effort standardization is effectively creating an unbiased relative abundance index, and this is particularly true in the SCP, where little operational data on setting procedures is available for the standardization analyses. The Taiwanese fleet in particular seems to have undergone a shift toward targeting swordfish. At present there is no compelling evidence to indicate that the SC Pacific swordfish fishery is over-exploiting the stock, but we do not consider the available data to be very convincing.

Data and research priorities for further reducing uncertainties are discussed for both the SWP and SCP swordfish populations.

1 Introduction

The first formal stock assessment for SW Pacific swordfish (*Xiphias gladius*) was presented to the Western and Central Pacific Fisheries Commission Scientific Committee (WCPFC-SC) in 2006 (spatial domain defined in Figure 1). The presentation consisted of 2 Methods Specialist Working Group working papers (Kolody et al. 2006a, and Davies et al. 2006), and a synthesis of results for the Stock Assessment Specialist Working Groups (Kolody et al. 2006b). Subsequent to the SC, a final report to the funding body was produced which we recommend as a single reference for the derivation of the final assessment (Kolody et al. 2006c). This paper represents an updated assessment that includes additional fisheries data and research that was not available in 2006. The WCPFC requested an update to the swordfish assessment in 2008, as one of the conditions associated with WCPFC Conservation and Management Measure 2006-3 (CMM06-3), which prescribes limits to the number of vessels allowed to target swordfish in the convention area south of 20°S. The Commission is planning to review CMM06-3 in relation to the new assessment.

The 2008 assessment attempts to address a number of concerns that were raised during and since the 2006 assessment, including:

1) The spatial domain is revisited in relation to the spatial domain of CMM06-3 (see Figure 1).

2) The 2006 MULTIFAN-CL assessment did not produce convincing estimates of migration within the South West Pacific, and this problem is revisited in relation to the revised spatial structure and new observations from Pop-up Satellite Archival Tags (PSATs) and conventional tagging.

3) Some comparative work on methods for estimating swordfish ages indicates that there is much greater uncertainty than was previously recognized. This has implications for growth rate, maturity and natural mortality assumptions.

These and other issues are discussed in section 3.2.

A swordfish assessment workshop was convened at the Secretariat of the Pacific Community (SPC) in Noumea (16-18 April 2008), to review the assessment data, new research and the assessment approach. Swordfish biologists and assessment experts were invited from various WCPFC member nations and other regional and international organizations. A number of working papers were produced in support of the workshop, and many of these have been revised for submission to the WCPFC-SC in 2008. A summary of the workshop discussions, and an agreed workplan for the assessment are included in Anon. (2008).

While this paper only describes the MULTIFAN-CL results, parallel work with CASAL was also undertaken in 2008 (Davies et al. 2008). A comparison and synthesis of the two approaches is planned for the WCPFC Stock Assessment Specialist Working Group.

1.1 Fishery History

For the purposes of this assessment, two main fishery regions are defined, the South-West Pacific (SWP) and the South-Central Pacific (SCP) (Figure 1). These regions are further subdivided into 4 areas and several sub-areas (zones) that were used to define homogenous fishery units (Figure 2). The swordfish catch history in the 4 areas are illustrated in Figure 3. Figure 4 separates the catch by area into the major fishing fleets. In this region, swordfish are caught almost exclusively by longliners. They are caught from the equator to around 50°S, with the highest catch rates and targeted fisheries between 20-40°S. Catches north of 20°S tend to be by-catch in tropical tuna fisheries, while catches south of 40°S tend to be predominantly very large females taken as by-catch in the Southern Bluefin Tuna (SBT) fishery.

In the SWP, swordfish have been taken primarily as by-catch in the Japanese tuna longline fisheries since the 1950s, with reported annual catches fluctuating around 2000 *t* over the period 1970-96. Japanese catches declined since the late 1990s, when the targeted Australian and New Zealand longline fisheries rapidly developed, with total annual catches averaging around 4000 *t* from 1997-2002. Catches have declined from 2002-7, with total catches in 2006-7 now around the levels observed prior to 1997. Fiji, Papua New Guinea, Vanuatu and New Caledonia have reported the largest catches among the Pacific Island nations. Standardized catch rates declined substantially for all the major fleets during the period from around 1999-2004. Since 2004, there has been a substantial increase in the Australian and New Zealand catch rates, however, the increase is not as evident in the Japanese fleet operating in the same general areas. Mean size composition has declined in the well-sampled Australian fishery since the mid 1990s.

SCP swordfish catches were lower than the SWP historically, but increased rapidly starting in the late 1990s and have been of comparable magnitude to the SWP since around 2000. Unlike in the SWP, SCP catches have not declined appreciably in recent years. The majority of the swordfish in the SCP have been taken as by-catch in the equatorial tuna longline fisheries. Japanese SCP swordfish have been landed since the early 1950s, and the Korean fleet began operating in the mid-1970s. Taiwanese fleets have taken substantial catches since ~2000. Beginning in 2004, the Spanish fleet has rapidly expanded, such that this targeted fishery recorded the largest catches of all nations in the combined SWP and SCP in 2006. French Polynesia, Cook Islands and Vanuatu represent the majority of the SCP Pacific Island catches. There is no compelling evidence for changes in size composition in the SCP catches, but available catch-at-size data are limited. Swordfish catch rates observed in the SCP suggest that swordfish abundance is stable or increasing in recent years. However, the operational level data available for conducting catch rate standardization analyses are limited, and some conflicting trends suggest that targeting changes are affecting CPUE trends for at least some of the fleets (notably Taiwan).

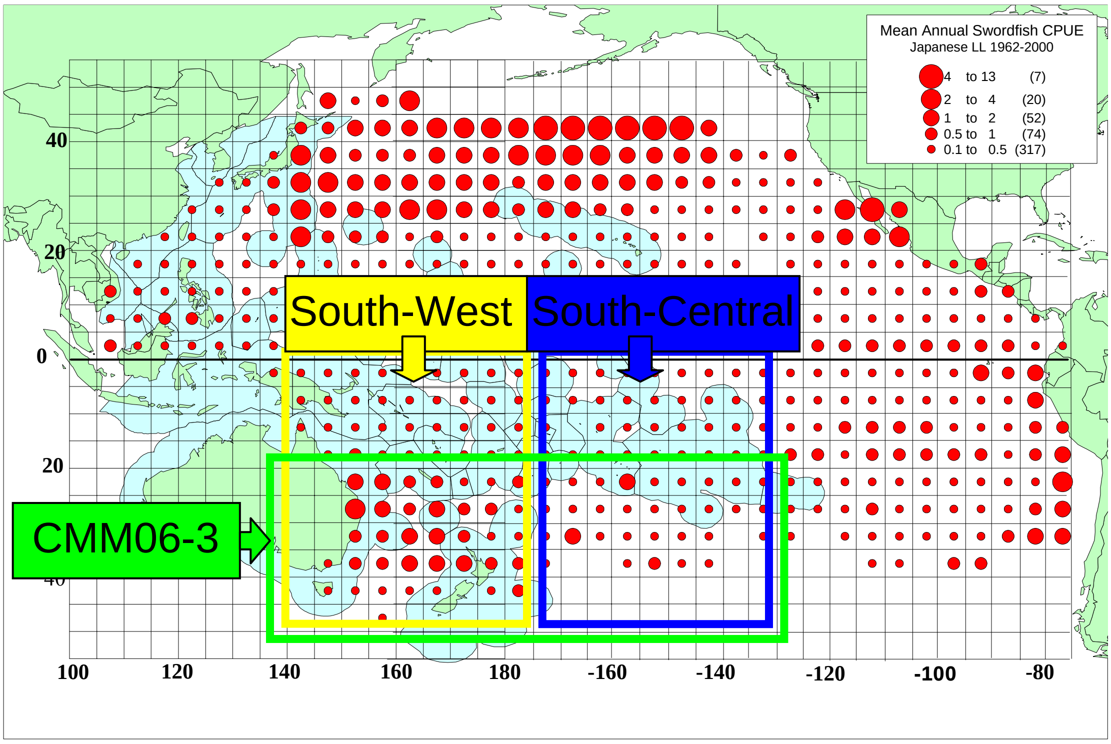


Figure 1. The South-West Pacific (SWP) and South-Central Pacific (SCP) regions as defined in the swordfish assessment, shown in relation to the region defined for Conservation and Management Measure 06-3. The boxes are superimposed on a map of mean nominal Japanese catch rates (1962-2000) which is thought to provide some indication of the relative abundance of swordfish throughout the Pacific.

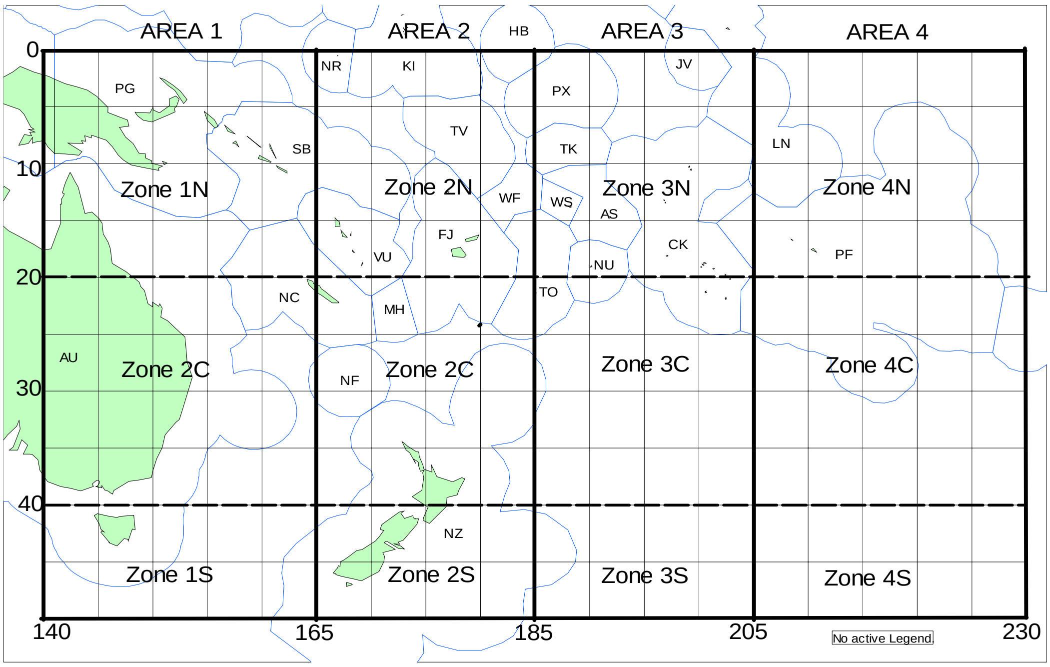


Figure 2. Spatial structure used in the 2008 southern WCPFC swordfish assessment. N, C and S refer to the North, Central and Southern zones of each area and are used to define fisheries. Areas 1-2 are referred to as the South-West Pacific (SWP); areas 3-4 are referred to as the South-Central Pacific (SCP) and combined areas 1-4 are referred to as the South-West/South-Central Pacific (SWP-SCP).

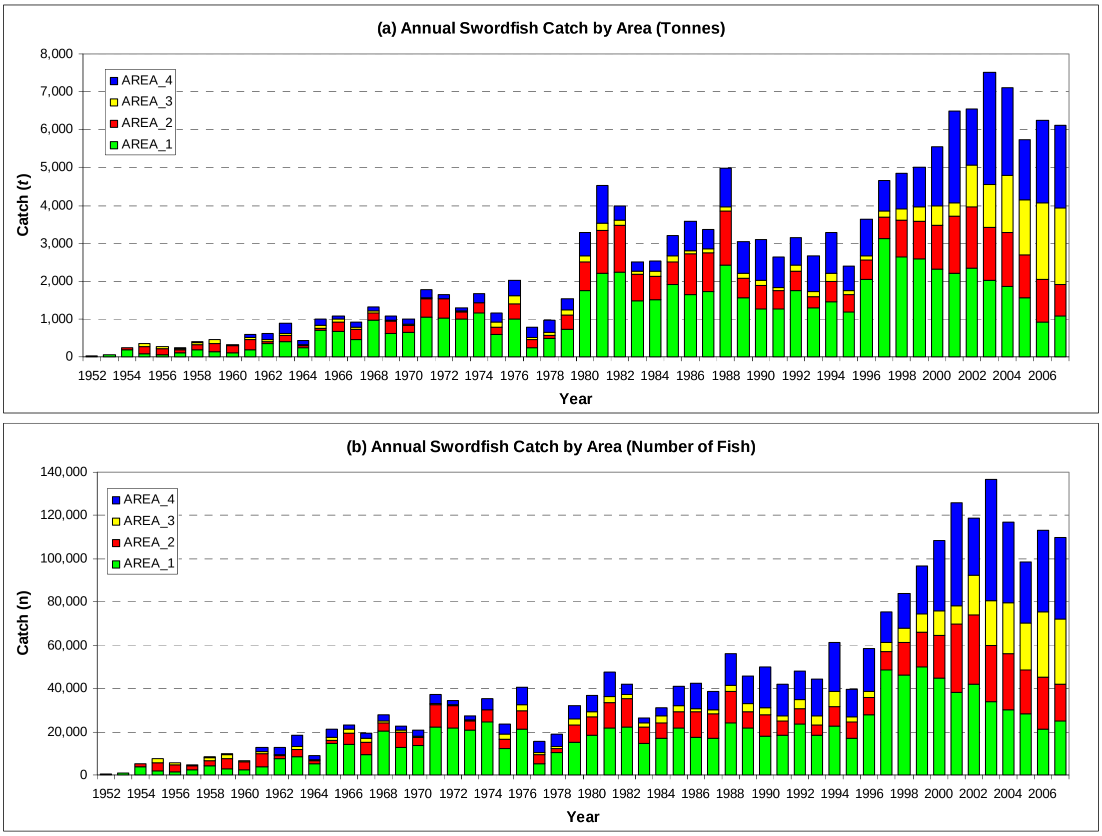


Figure 3. Total swordfish catch in mass (top panel) and numbers (bottom panel) for swordfish in the combined South-West and South-Central Pacific 1952-2007 (note that the 2007 data are incomplete for some fleets and assumed to be equal to 2006 levels). Areas are illustrated in Figure 2.

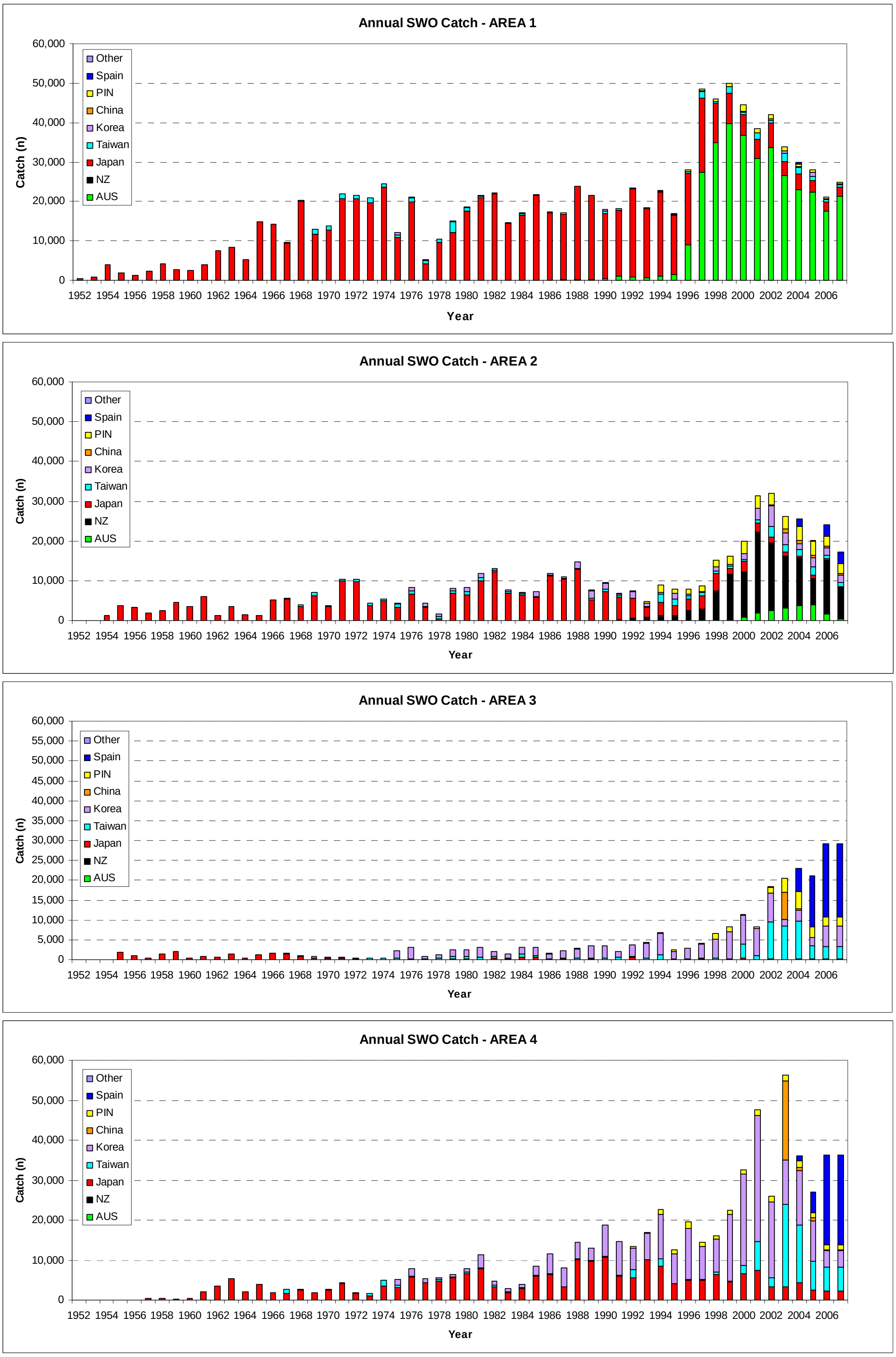


Figure 4. Swordfish catch history (numbers) in the South-West (areas 1-2) and South-Central (areas 3-4) Pacific by fishing nation. Areas are illustrated in Figure 2.

1.2 Swordfish 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 (Figure 1). 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 "$\supset$"-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 SCP represented a population intermediate between the SW and SE, but it was recognized that sample sizes in the SCP region were not sufficient to be conclusive (Michael Hinton, IATTC, Pers. Comm.).

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.

Swordfish are sexually dimorphic 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 SWP (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 methods used among laboratories has suggested that there remains a large degree of uncertainty about some of the basic biology of this species (Young et al. 2008).

2 Data

2.1 Fishery Data

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 2008. Much more detailed summaries and analyses of the catch, effort and size composition data are provided in Campbell (2008), and catch rate standardization analyses are detailed in Campbell et al. (2008).

2.2 Catch Data

Swordfish catches are commonly reported in numbers and are illustrated by area and fleet in Figure 3 and Figure 4. The catch data used in the SWP assessment data are essentially the same as used in 2006, with the following exceptions:

- Three additional years of data were obtained for most fleets. Australian and New Zealand catch and effort data included 2007 (except the last quarter in the case of NZ), all other fleets included only 2006 (2006 may be incomplete for some fleets). Missing catch data from 2007 was assumed to be identical to 2006; no substitution was made for missing effort.
- In 2006, logbook data was used to estimate the New Zealand catches and this resulted in a bias approximately 25% lower than the estimates provided through the quota management system. Quota management data were used in 2008.
- There remains some uncertainty about the separation of NZ domestic and charter fleet catch data (which might mean that the NZ domestic catch is over-reported by 1-2%). This does not affect the size composition data.
- The New Zealand domestic fishery instigated a comprehensive port sampling program in 2006, which resulted in a large number of size composition samples in 2006-7 relative to previous years.

As swordfish have historically been a by-catch species, there may be catch reporting problems related to discarding, but we have no evidence to suggest that this is an important problem in this fishery.

2.3 Effort and CPUE Data

Pelagic fisheries stock assessment models are generally dependent on the use of catch rates from commercial operations as relative abundance indices. If catch rates cannot be effectively standardized to remove the effects of factors that are confounded with abundance, then the relative abundance indices will likely not be reliable, and one cannot have much confidence in the assessment model results. For targeting fleets, there is always the possibility that efficiency is increasing in ways that are not recorded in logbooks. Equivalently, by-catch fleets might be changing their operations in ways that incidentally change swordfish catchability. In the SWP and SCP assessments, data were only obtainable from three nations with which it was considered possible to attempt estimating informative abundance indices – Japan, Australia, and New Zealand. Important operational level data was either not available for other nations, or the spatial and temporal coverage of the fleets was not sufficient to provide an informative index.

Standardized effort series were used in the assessment on a quarterly time-step. Annual CPUE trends (seasonality removed for clarity) for the SWP are shown in Figure 5. From these plots, the Australian and New Zealand fleets suggest very similar relative abundance trends in areas 1 and 2, with similar declines from 1997-2003, and similar increases from 2003-7. In contrast, the Japanese fleets show a continuous (though noisy) decline from 1997-2006. It is not clear which of the trends is closer to reality, and this is discussed further in section 3.2.14.

Standardized Japanese catch rates from areas 1-4 are shown in Figure 6. Unlike the SWP (areas 1-2), the SCP (areas 3-4) catch rates suggest stable or increasing trends. This is further suggested by the Taiwanese and Korean nominal catch rates (Figure 7). The Taiwanese catch rates in particular show a rapid increase starting ~2000, which suggests a major targeting shift toward swordfish.

We note that standardized catch rates for the Spanish fleet for 2004-6 are provided in Mejuto et al. 2008b, and appear to be stable over this period. Unfortunately, the spatial structure used in this CPUE analysis extended beyond the assessment domain, and there were concerns about the validity of the analytical methods used to account for targeting (Anon. 2008). However, the Spanish fleet represents a promising source of information for future CPUE analyses, and we encourage greater collaboration in the future.

The April 2008 assessment workshop (Anon. 2008) revealed that logbook data from the Taiwanese fleet has been recorded at Pago Pago historically, and this operational level data may be obtainable through collaborative studies with the U.S.A. in the future.

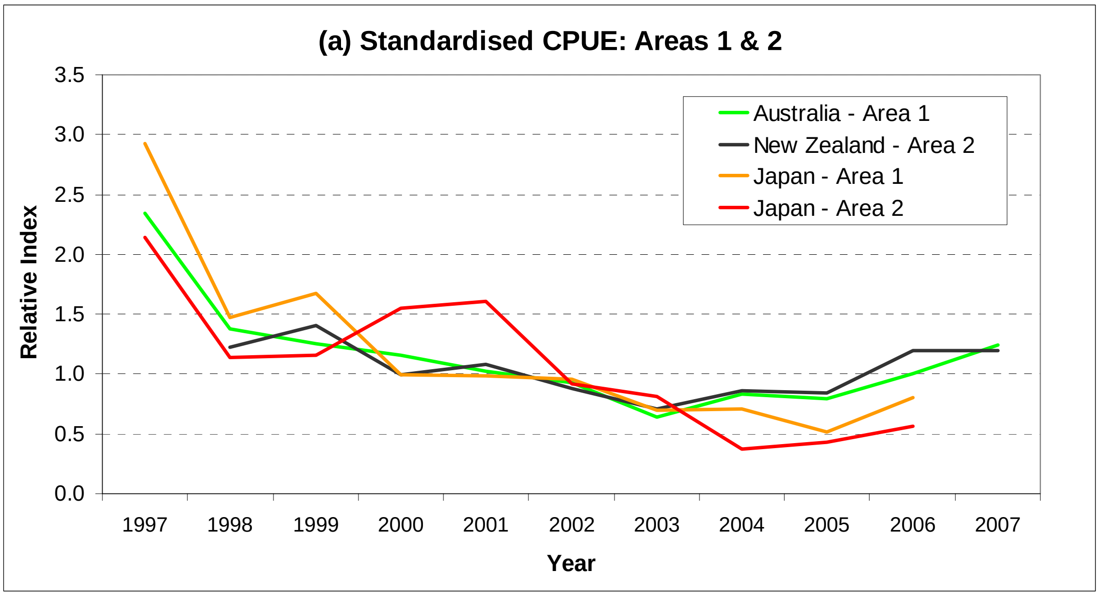


Figure 5. Comparison of standardized catch rates for South-West Pacific fleets from 1997-2007 for the central zone of areas 1 and 2 as defined in Figure 2 (normalized to a mean of unity).

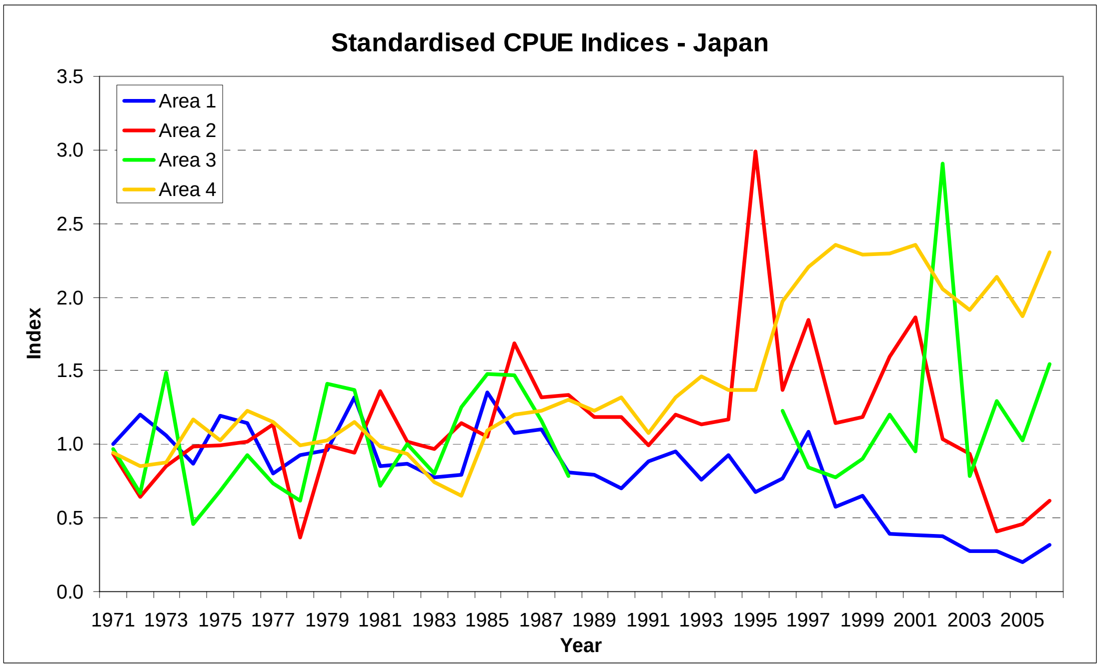


Figure 6. Comparison of standardized catch rates for the Japanese fleet for Areas 1-4 (normalized to a mean of unity).

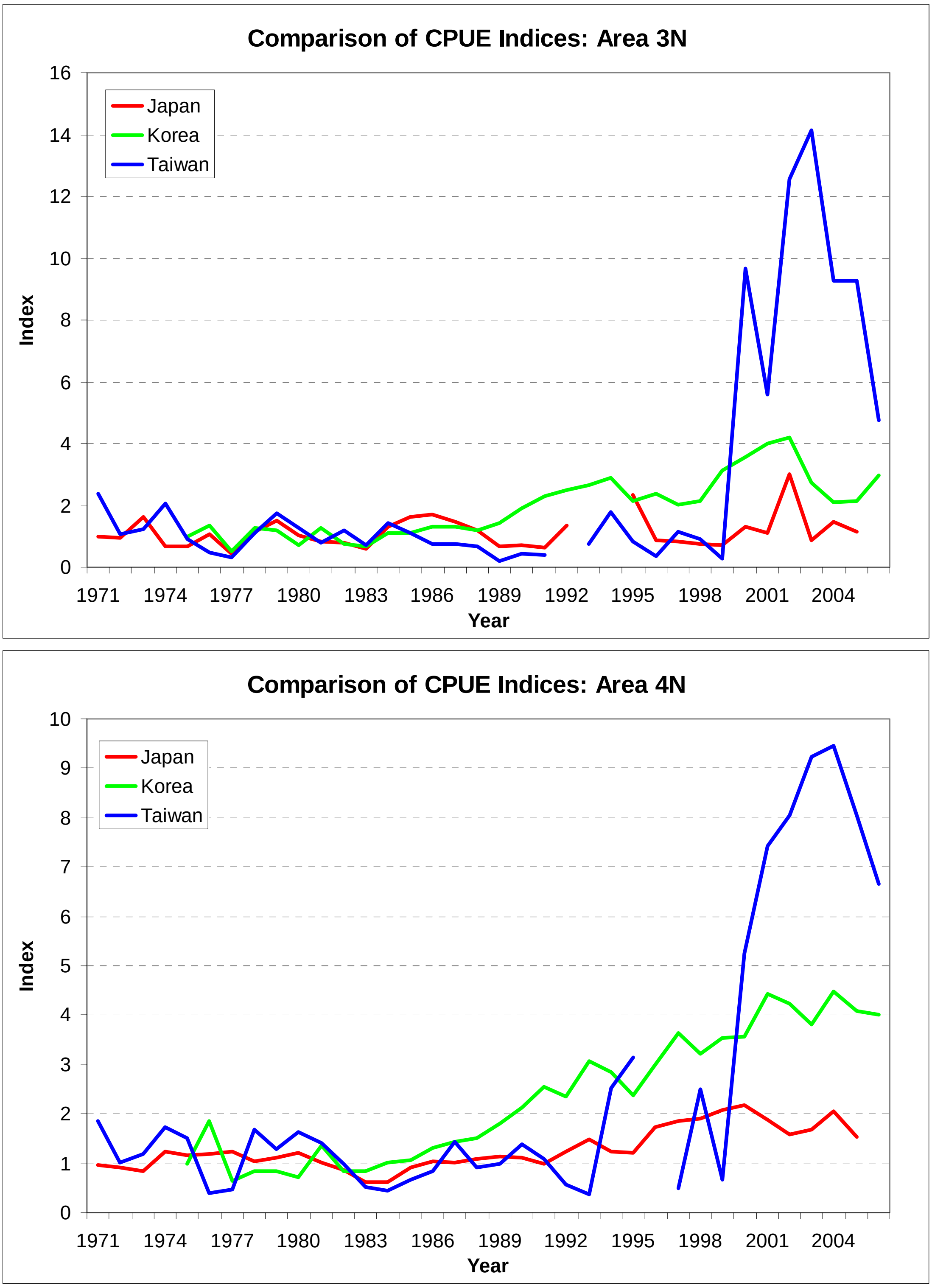


Figure 7. Comparison of DWF nominal catch rates from the South-Central Pacific (the northern zones of Areas 3 (top panel) and 4 (bottom panel)). Areas are defined in Figure 2.

2.4 Size Composition Data

Swordfish catch-at-size is not well sampled for many of the fleets in the assessment area (e.g. Figure 8). Australia has samples about 70% of the domestic catch since 1997, and New Zealand implemented a comprehensive port sampling program in 2006. With the exception of the short time series of the Spanish fleet, there is very little sampling from the SCP. In July 2008, the assessment team became aware that additional Spanish size data from 2005-6 had been provided to the SPC, but these data were not loaded into the SPC database, and hence were not provided in time for inclusion in the assessment. The absence of these data are not expected to make much difference to the current assessment because the 2004 Spanish data were included (which informs the selectivity estimation), and the mean size composition in these data has not changed noticeably in 2005-6.

Figure 9 illustrates trends in mean size composition over time. The Australian fleet is the most heavily sampled, and shows strong evidence for continuously declining sizes over time. When partitioned on a finer spatial scale, there are patterns in size composition evident within the Australian fishery, however, there is no evidence that the overall declining size trend is a result of a trend in the spatial distribution of effort (Campbell 2008).

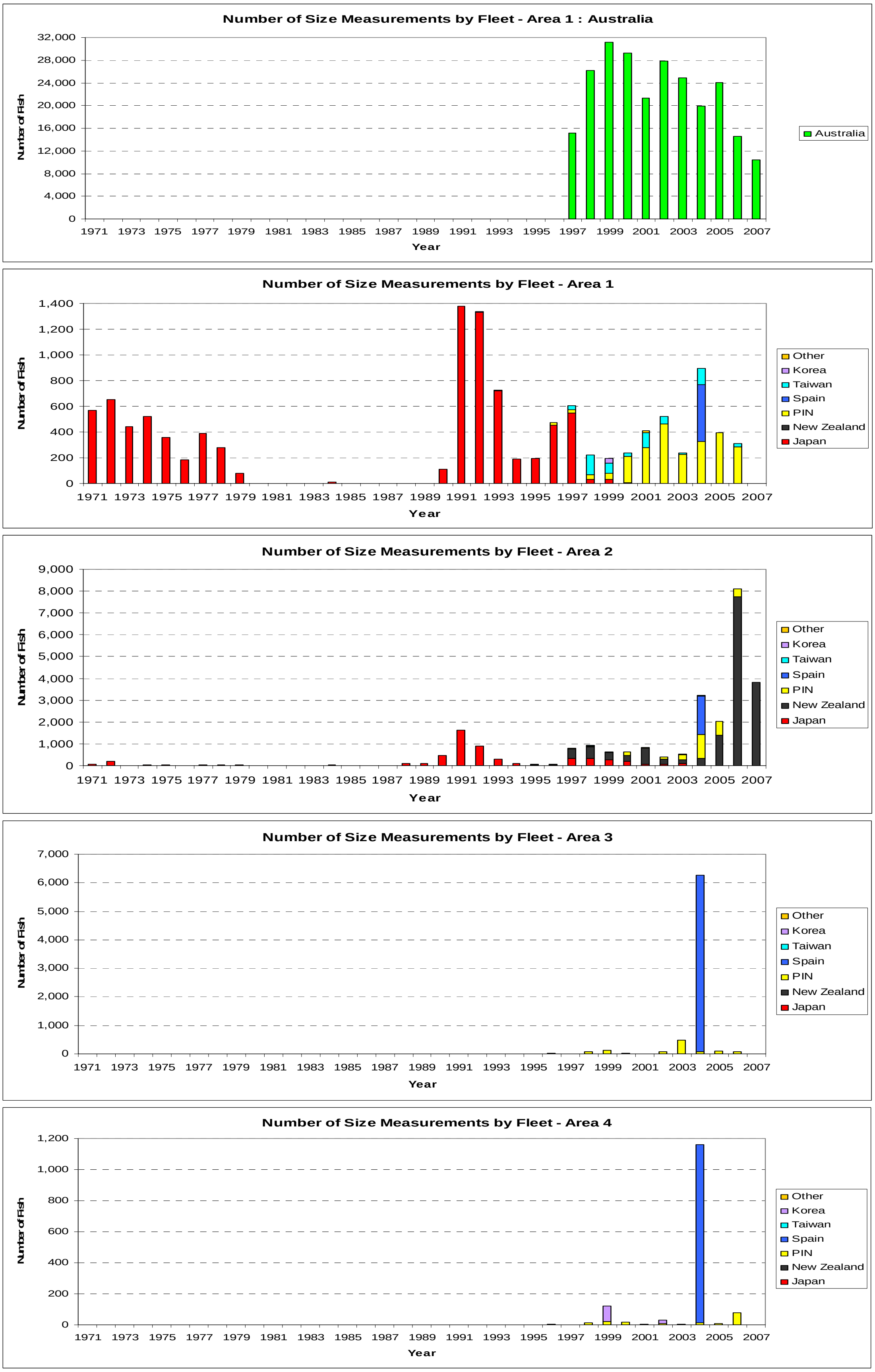


Figure 8. Sample sizes for catch-at-size sampling in the SWSC Pacific by nation. Australian sizes are in mass, all others in length (note that scales differ by area).

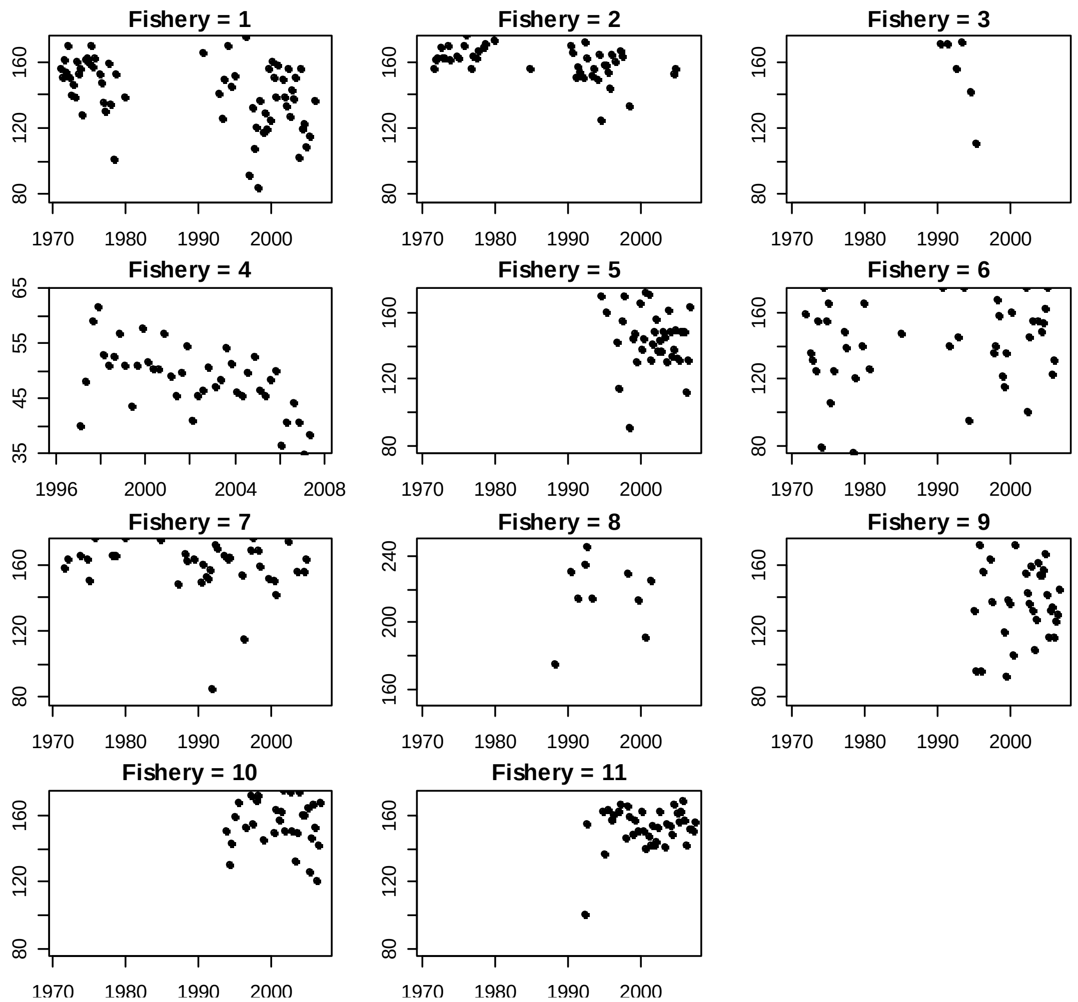


Figure 9. Mean size composition of swordfish catches over time for SWP fleets. Note that the Y-axis scales differ for fishery 4 and 8 relative to the others. Fishery 4 (Australian area 1) is in trunked mass (kg), all other plots are in length (cm).

2.5 Fisheries independent research data

Fisheries independent swordfish research has yielded important insight in three areas since 2006:

- A number of PSAT tags have been deployed by Australia and New Zealand, providing inferences on short term movements, and a few conventional tags have been recovered with longer durations at liberty (up to 6 years) (Figure 10). Tag inferences are discussed in the sections relating to spatial structure and migration assumptions below (3.2.1 and 3.2.10).

- Spatial patterns of catch characteristics in the Spanish fleet have yielded some interesting insights about population demographics. These are discussed further in the section on spatial assumptions (3.2.1) below.

- A comparison of swordfish age estimation methods has revealed substantive differences among labs that do not seem to be resolvable without further research to directly validate the interpretation of fin spine annulus counts. This has important implications for other assumptions as well and is discussed in the sections relating to growth, maturity and mortality assumptions below (3.2.7-3.2.9).

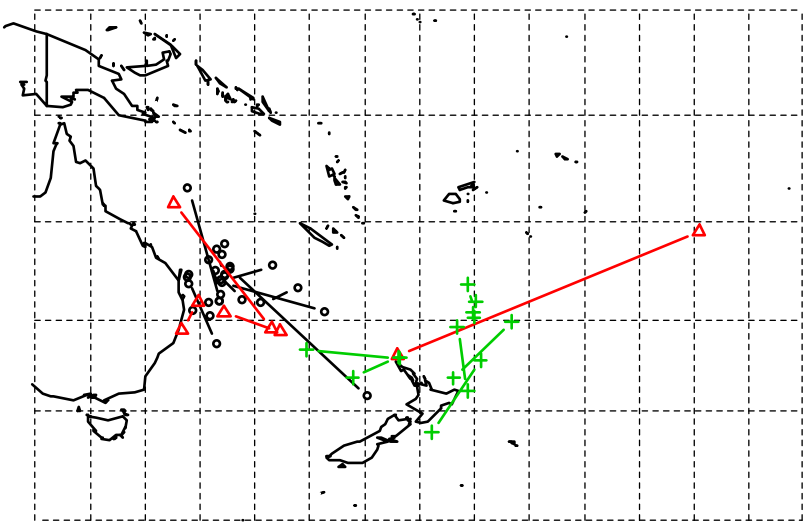


Figure 10. Release and pop-off (or recapture) points for Australian (black circles) and New Zealand (green "+") PSAT tags and conventional tags (red triangles), for tags at liberty between 60 days and 6 years (Figure 8 from Kolody and Davies 2008)

3 Modelling Methods

Recognizing the fact that fisheries assessment problems are almost always over-parameterized (e.g. Schnute and Richards 2001), we would be reluctant to ever assign much credibility to any individual model result. In general, we view complicated integrative population models as tools for exploring the interactions among data and assumptions, identifying conflicts, quantifying robust patterns, and identifying major uncertainties and sensitivities.

3.1 MULTIFAN-CL Stock Assessment Software

Continuing with the general approach used in 2006, the 2008 swordfish assessment involved parallel modelling approaches to ensure a more robust final result. This paper describes the approach and results using MULTIFAN-CL, while Davies et al. (2008) describes an attempt at a CASAL (e.g. Bull et al. 2003) assessment.

MULTIFAN-CL (primarily developed by Otter Research, Ltd.) has a rich set of features tailored for pelagic fisheries assessment and a substantial track record of applications in a spatially-disaggregated context (e.g. Hampton and Fournier 2001). It is a flexible, integrative, numerically efficient, assessment modeling framework initially developed for, and routinely applied to, the assessment of tuna species of the Western and Central Pacific Ocean (e.g. Hampton et al. 2006a,b). Most technical specifications, dynamic equations and statistical assumptions are documented in Kleiber *et al*. (2005).

MULTIFAN-CL provides a flexible statistical framework and efficient function minimization routines to estimate model parameters and reference points derived from these parameters. Parameter estimation consists of minimizing an objective function including (negative log-) likelihood terms, prior probability distributions and smoothing penalties. In addition to estimating the Maximum Posterior Density (MPD), MULTIFAN-CL can calculate the statistical uncertainty associated with parameter estimates using the inverse-Hessian matrix and Delta-method normal approximation and likelihood profiles for many quantities of interest.

The swordfish models were fit in a series of 10 phases in which an increasing number of parameters were estimated in successive phases, with all free parameters fit in the last phase (see SWP bash script in Attachment 1). MULTIFAN-CL also invokes a number of internal strategies in the early stages of the minimization that are not well documented. Together, these processes seem to result in a robust minimization that rarely (in the 2008 swordfish applications) led to results that were identifiable as obviously implausible. However, we note that there were some strange results in the preliminary trials using the 2006 spatial structure with the new data in 2008 (Anon. 2008).

A number of tests were undertaken to examine the probability of MULTIFAN-CL finding alternative minima (for the SWP models). These included: i) altering the temporary F target in the initial phase of the minimization (1%, 10% (default), 50%), ii) Adjusting total population and recruitment scaling factors in the second phase of the minimization (by a factor of 0.1, 1 (default), and 10), iii) changing the number of iterations in the intermediate phases (though not the first or final phase) of the minimization (250 (default), 25, 3). In most cases, MULTIFAN-CL arrived at the same solution (to within 0.0001 likelihood units, and 4+ significant digits for the estimated quantities examined). From these trials, the only deviation resulted when the number of iterations in the intermediate phases were reduced to 1% (3 iterations) of the default setting. In this case, MULTIFAN-CL yielded a result that we would have concluded converged successfully (on the basis of the small gradients), though it is possible that the maximum iteration setting (5000) in the final phase was reached. In this case the minimum objective function value was ~10 likelihood units off of the best solution, and estimated quantities were within 4% of the best solution. It seems that the minimization is impressively robust under the conditions tested, and the results are plausibly consistent with the data. Hence we expect that the results are useful, whether or not the global minimum was always identified.

Each SWP swordfish model included 1977 estimated parameters. However, it is important to realize that most of these parameters are not really free parameters in the sense of some other models. The effort deviations account for the majority of parameters. If one were to use an equivalent model assuming that catch in numbers was known perfectly (which is essentially what these models are doing anyway), and treating the effort deviations purely as CPUE observation errors, then the number of estimated parameters is greatly reduced. In this particular model, additional parameters were either tightly constrained by priors (stock recruitment relationship), or bounds (growth curves), or related to future projections. The core dynamics of the SWP models are primarily driven by the following parameters:

- Recruitment deviations - 1 per year
- selectivity – 5 cubic spline nodes for each of 4 selectivity groupings
- catchability – mean plus seasonal deviations for each of 3 fleets with informative CPUE series (noting that catchability is shared for the two Japanese fleets)
- functional relationship of SD on length-at-age – 2 parameters

Thus the effective number of parameters for this group of SWP models is more like 93 than the official number of 1977.

MULTIFAN-CL is a complicated and continuously evolving piece of software, and as such, it is not surprising that code and documentation errors continue to be identified at regular intervals. The underlying dynamic equations as used in most applications seem to be stable, robust and consistent with similar software. This assessment was conducted with the same version of MULTIFAN-CL that was used in 2006 (16 Jun 2006 Windows build). While newer versions exist, there were implementation problems with the swordfish application that could not be resolved by the authors in time for the new version to be adopted for the 2008 assessment. SPC staff have indicated that developments and bug fixes since this 2006 release do not seem to have any substantive implications on the model features that were used in this assessment (John Hampton, SPC, pers. comm.). In July 2008, a bug was identified which affects model specifications in which the stock recruitment curve steepness exceeds 0.95 (Simon Hoyle, SPC, pers. comm.); this was not a problem for any of the results presented here.

3.2 Assessment Assumptions

This assessment is underpinned by the recognition that assessment models inevitably involve somewhat arbitrary constraining assumptions, and the stock status results may be highly sensitive to these assumptions (e.g. Schnute and Richards 2001). As such, we have made an effort to explore a large range of alternative combinations of plausible assumptions to provide an indication of the model selection uncertainty. In sections 3.2.1 - 3.2.13 we describe the assumptions, with an attempt to justify them. Multiple assumptions listed as bulleted points indicate that alternative assumptions were being tested. The manner in which the assumption combinations were combined is discussed 3.2.14 and summarized in Table 2 and Table 3.

3.2.1 Assessment Spatial Structure

Kolody and Davies (2008) review the evidence and arguments relevant to the spatial domain and internal structure adopted for this assessment. Further discussion is recorded in the April 2008 workshop report (Anon. 2008).

The overall assessment domain was derived after consideration of larval distributions, genetic connectivity studies, conventional and PSAT tag deployments, fishery characteristics (including distributions and seasonal patterns in catch, CPUE, and size composition) and the WCPFC request to encompass the broader South Pacific convention area in the assessment.

The SCP swordfish population is a data poor region with uncertain migratory links with adjacent regions in the Pacific. In 2006, it was recognized that the available data in the SCP would not likely provide any means for estimating the fishery impact on the population, whereas the SWP was recognized as being plausibly describable as a relatively discrete sub-population. In 2008, a formal attempt was made to estimate standardized catch rates, compile size composition data, and examine the SCP data in the context of an integrated assessment that included the combined SWP and SCP area. However, it was again recognized that the SCP was problematic and the 2008 swordfish assessment workshop (Anon. 2008) noted:

> *Given the lack of compelling evidence for a single stock across all 4 regions of the southern WCPO, and the lack of reliable swordfish abundance indicators in regions 3 and 4, the Workshop recommended that the primary focus of the 2008 assessment should be on the swordfish resource located in the southwest Pacific (Regions 1-2), and that additional sensitivity analyses should be undertaken to include regions 3 and/or 4 (with the northern zones excluded) if possible.*

Despite the latter recommendation from the workshop (i.e. to exclude the northern zones), the decision was made to include the northern zones in our exploration of the SCP. There does not seem to be any compelling biological justification for separating the northern and central zones, and further analyses indicated that the only standardized catch rates that were worth considering from the SCP at this time were generated from the Japanese fleets operating in the northern zones (Campbell et al. 2008).

The internal spatial structure of the swordfish assessment was substantially changed from that adopted in 2006. Problems with the spatial structure adopted in 2006 included:

1) The complicated spatial structure in 2006 was adopted to accommodate the differing trends in exploitation patterns, CPUE and size composition that seemed to be occurring within the SW Pacific. However, when the data were standardized and summarized at the pre-determined scale, evidence for divergent patterns within the SWP were much less apparent (and to some extent this may reflect an absence of adequate data rather than a truly homogenous population).
2) The 2006 model structure had considerable freedom to estimate migration (variable by area, season and age), but all of the movement estimates in 2006 were indirect inferences (i.e. no tagging). The model tended to estimate biologically questionable movement patterns (potentially including spatial and temporal refuges for ‘cryptic biomass’).
3) There was a confounding of seasonal catchability and seasonal migration that could not be resolved (i.e. seasonal CPUE patterns between fleets operating in the same area differed, such that it was not possible to conclude how much of the cyclic pattern actually represented migration).
4) The southern area (SBT-targeting) fishery has unique characteristics, such that it was difficult to link abundance between the northern and southern areas (e.g. through shared catchability), and the model estimates of abundance (or exploitation rates) in this area were often thought to be unrealistic.
5) Exploratory comparisons of homogenous mixing and foraging site fidelity models (using CASAL and production models, but not MULTIFAN-CL) indicated that both sets of migration assumptions seemed to be consistent with the data.

The new spatial structure (illustrated in Figure 2) is thought to be preferable to that used in 2006 because:

1) PSAT tags in the SW Pacific and elsewhere suggest that there are directed seasonal migrations between spawning and foraging grounds, and in the SWP this seasonal migration can be represented by seasonal catchability (and potentially selectivity), without the need to explicitly partition the areas.

2) PSAT and conventional tags provide a means for estimating east-west diffusive movement. While preliminary, these estimates are likely to represent an upper bound of mixing rates, and using these values directly in the assessment models provides a strong structural constraint to the dynamics. This is discussed under section 3.2.10.
3) The longitudinal stratification facilitates a direct comparison between the aggregate assessment results from the 2006 assessment and the SWP component of the 2008 assessment. It is easy to remove one or both of the more eastward extensions of the model domain in relation to new evidence.

The two-tiered approach to the assessment (i.e. Table 2 and Table 3) was defined in relation to the spatial stratification in Figure 2 and the fishery definitions in the following section:

- SWP assessment (A12F11, Table 2) consists of Areas 1-2 and fisheries 1-11
- combined SWP-SCP assessment (A14F18, Table 3) consists of Areas 1-4 and fisheries 1-18

3.2.2 Fishery Definitions

Table 1 defines the 18 fisheries used in the MULTIFAN-CL models of the SWP and SCP. The quality and amount of data varies considerably among fisheries and a number of smaller or similar fleets were aggregated (i.e. similarity assumed on the basis of catch size frequency distributions if possible). Only 6 fisheries were assumed to have informative CPUE series (adequately standardized effort); 4 in the SWP and 2 in the SCP. Many of the 18 fleets were assumed to have identical selectivity (shared parameters in the model estimation). Some of these fleets are active in the same area, and hence the fleets are effectively aggregated (but separable for the purposes of exploring management options). Campbell 2008 describes the size composition data for the available fleets, and illustrates that in most cases the catch size frequency distributions are either very similar or poorly sampled. An obvious exception is the southern (SBT-targeting) fleets which catch very large individuals. Some of the other southern fleets may represent a mixture of northern and southern characteristics. On this basis, 4 different selectivities were defined and estimated independently.

Table 1. SWP and SCP fishery definitions in the assessment models. Areas and sub-areas are illustrated in Figure 2. Selectivity and catchability groups identify fisheries with shared parameters (e.g. fishery 2 and fishery 7 both belong to catchability group 'A' and hence catchability parameters are shared in the model).

Fishery Number	Area	Sub-area (zone)	Catchability Group	Selectivity Group	Fishing Nation(s)
South-West Pacific					
1	1	N	n/a	a	Japan (plus other DWF)
2	1	C	A	a	Japan (plus other DWF)
3	1	S	n/a	b	Japan (plus other DWF)
4	1	N+C+S	B	a	Australia
5	1	N+C	n/a	a	Pacific Island Nations
6	2	N	n/a	a	Japan (plus other DWF)
7	2	C	A	a	Japan (plus other DWF)
8	2	S	n/a	c	Japan (plus other DWF)
9	2	N	n/a	a	Pacific Island Nations
10	2	C	n/a	a	Pacific Island Nations
11	2	C+S	C	d	New Zealand
South-Central Pacific					
12	3	N	A	a	Japan (plus other DWF)
13	3	C+S	n/a	a	Japan (plus other DWF)
14	3	N	n/a	a	Pacific Island Nations
15	3	C	n/a	a	Pacific Island Nations
16	4	N	A	a	Japan (plus other DWF)
17	4	C+S	n/a	a	Japan (plus other DWF)
18	4	N	n/a	a	Pacific Island Nations

3.2.3 Catch Rate Assumptions (effort deviations, catchability, and relative areas)

These types of stock assessment models tend to perform poorly in the absence of reliable relative abundance indices (e.g. as demonstrated with simulations in Kolody *et al*. 2004). It follows that we would also expect poor model performance if the abundance indices are poorly fit by the model (i.e. whether or not they are reliable). The conflicting recent trends in the Australia/New Zealand vs: Japanese CPUE trends (Figure 5) raises a problem in that (at least) one of them has to be somewhat wrong. To assume that they are both equally correct and diverging through observation error alone results in an averaging of series. We consider it more likely that one set of trends is probably more correct than the other, but we do not know which. Three alternative weighting scenarios were employed in the model uncertainty grid to reflect this situation:

- UA1 - Both series equally reliable
- UAJ - Australia/New Zealand more reliable than Japan
- UJA - Japan more reliable than Australia/New Zealand

The SD of the (natural log) effort deviations corresponding to these scenarios is listed in Table 2 and Table 3. These values are approximately equivalent to the CV of the CPUE observation error. Effort series for all other fleets were considered uninformative and set to missing.

In WCPO tuna assessments, catchability for the Japanese longline fleets is usually shared across areas. The shared catchability implies that the same CPUE in two different areas corresponds to an equivalent density (i.e. fish per unit of surface area) and allows the relative abundance of different regions to be linked. However, there is a further step involved in relating density to abundance. The (relative) area (or volume) of each region is required to interpret the relative density as relative abundance (i.e. number = density X area). However, fish are not usually homogenously distributed within a region, and the "effective" area of the fish distribution might be considerably different from the actual geographical area. Estimating the effective area of a region is problematic if the spatial and temporal coverage of the effort represents a small portion of the fish distribution. Fisheries-dependent data (and many surveys) are often plagued by inadequate coverage, which leads to philosophical debates about fish density in unfished areas. For the swordfish assessment in 2006, three relative area options were investigated, related to 1) the geographical surface area as defined on a map, 2) the maximum extent of the historically fished area, and 3) the maximum range in which swordfish were caught historically. The 2006 assessment was not very sensitive to these assumptions. Hence, in 2008, it was simply assumed that the relative areas for the purpose of CPUE applicability were equal among the 4 areas in Figure 2. The southern zones of the SCP might not have been fished as heavily as the SWP (because there are not significant numbers of SBT in the SCP), so we cannot be sure of the swordfish density in this region. However, swordfish density is not thought to be high in the southern regions of the SWP either, so this should not introduce a large error.

3.2.4 Fishery Selectivity Assumptions

Selectivity was assumed to be constant over time for all fisheries, and was parameterized as a cubic spline function with 5 nodes. The revised spatial structure was intended to account for migration using seasonally variable selectivity if required. However, this was not pursued, in part because 1) the model diagnostics examined did not show obvious biases relative to the size composition data that are available, and 2) the fisheries with good size composition data tend to have a strong seasonal pattern in catch anyway (i.e. if not many fish are being caught outside of the main season, the size bias in the off-season will not have much influence). In the 2006 assessment, it was found that assessment results were sensitive to alternative selectivity assumptions, and two options were again pursued in 2008 (Table 2 and Table 3):

- SM – selectivity non-decreasing with age
- SF – selectivity unconstrained (dome-shaped usually results in this case)

In 2006, the unconstrained models tended to prefer dome-shaped selectivity, however both assumptions could produce results that were plausibly consistent with the data (with the appropriate combination of other assumptions). There is evidence that swordfish have size-specific distributions (likely related to sex dimorphism), with larger individuals caught disproportionately in the south. In the revised spatial structure, selectivity is clearly influenced by availability, and the large fish in the southern zone would be expected to be less vulnerable to the fleets of the northern and central zones (for at least part of the year). Hence, we did not think it would be appropriate to impose a non-decreasing selectivity constraint on the northern and central fleets with the revised spatial structure. We did however explore the effects of the non-decreasing constraint on the southern SBT-targeting fleet (fishery 8, which catches only very large swordfish).

3.2.5 Catch-at-Size Sample Characteristics

MULTIFAN-CL assumes that length-at-age is normally distributed about the mean, and uses a robust likelihood term to reduce the influence of outliers when fitting the size frequency observations. Model predictions are based on an assumed mean growth curve described in section 3.2.7. The length-mass relationship was estimated from New Zealand observer data, and based on lower jaw fork lengths (cm) and trunked mass (kg): mass = 7.62e-7(length)$^{3.49}$.

There are a number of reasons why it might not be appropriate to use the actual sample sizes from the length and mass frequency distributions as inputs to the model likelihood terms. In these models: i) the assumption of constant selectivity over time is probably not entirely valid (e.g. species targeting shifts probably have some effect on selectivity), ii) swordfish growth curves are currently highly uncertain (plus there are complicating factors of sexual dimorphism and within year growth) iii) many of the size samples are small and unlikely to be random samples from the whole fishery, iv) with respect to the mass data – different processors use different methods, resulting in differences of up to 10% suspected for the trunked mass. We considered 2 down-weighting schemes in the model uncertainty exploration (e.g. Table 2 and Table 3):

- ES5 - sample size = n/5
- ES20 - sample size = n/20

There is also a maximum sample size of 1000 implemented before the down-weighting is applied.

3.2.6 Stock Recruitment

Recruitment was assumed to occur once annually (quarter 1). A Beverton-Holt stock recruitment relationship was assumed, with all mature spawners contributing to the spawning biomass irrespective of area. Because of the general difficulty in reliably estimating stock recruitment curves, different levels of recruitment compensation were imposed in the model uncertainty grid via tightly constrained priors (e.g. MULTIFAN-CL beta distribution parameters 9000, 1000 for steepness 0.9). In 2006, 3 steepness (*h*) options were explored (Figure 11). All values were in reasonable agreement with the data (depending on the other model assumptions), but the higher values were considered more plausible on the basis of life history arguments, and signs of apparent stock recovery in other swordfish fisheries that experienced effort reductions (e.g. Ortiz 2005 describes rebuilding in the North Atlantic). Accordingly, only the two more productive values were considered in 2008:

- h65 - h = 0.65 (moderate degree of recruitment compensation)
- h90 - h = 0.9 (high recruitment compensation)

In the SWP models, the final MPD estimates tended to be slightly higher than the mode of the priors. In the combined SWP-SCP models, the MPD estimates were often very different from the mode of the priors as described in the results.

Two different assumptions were explored with respect to the magnitude of interannual recruitment variability:

- r1 – SD on the log recruitment deviation = 0.1 (CV ~ 10%)
- r5 – SD on the log recruitment deviation = 0.5 (CV ~ 50%)

The higher value is considered to be more plausible for pelagic fish populations in general. However, there was a concern that the relaxed recruitment constraint might result in highly irregular and misleading recruitment time series because of the small number of non-representative size samples. The constrained recruitment deviation assumption was tested as an alternative in the uncertainty grid, which would ensure that the recruitment time series was not unduly influenced by poor size sampling, and would yield results that conformed with stock recruitment assumptions. This of course raises the opposite concern, i.e. the imposition of a strong stock recruitment relationship which might not be supported by the data. The primary intent of exploring both options in the uncertainty grid was to find out whether the stock status results were sensitive to this assumption.

In the SWP, recruitment was split equally between areas 1 and 2. In the combined SWP-SCP models, two options were explored for the distribution of recruitment:

- RS1 - Recruitment was split evenly among areas 1-4
- RS2 - The recruitment split among areas 1-4 was estimated with regional deviations over time estimated

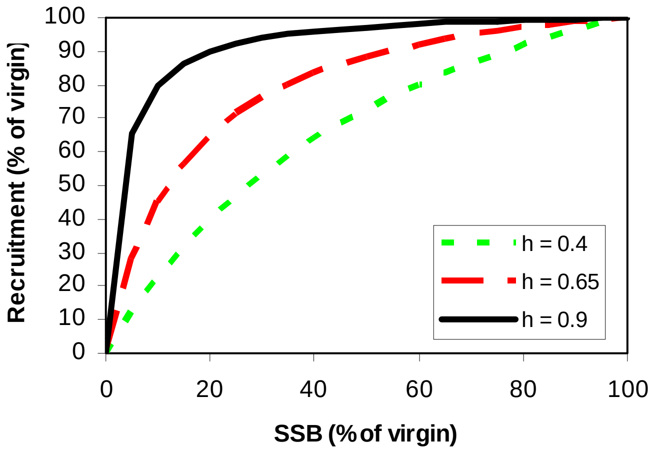


Figure 11. Three levels of stock recruitment curve steepness (*h*) assumed in the model uncertainty grid in 2006. Only the higher values *h* = 0.65 and 0.9 were used in 2008.

3.2.7 Growth Curves

Young et al. (2008) describe some recent work on the comparison of age-estimation methods from biologists at CSIRO (Australia) and NMFS (Hawai'i). On the basis of this work, it is appropriate to consider that SW Pacific swordfish may be growing and maturing at a rate that is much faster than had been assumed in 2006 (Figure 12). Without direct age validation studies, it remains unclear which method of interpreting fin spine counts is more appropriate. New growth curves have not been estimated for the Australian fin ray samples to date, however, visual inspection suggests that the Hawaiian growth curves described in DeMartini et al. (2007) seem to fit the alternative readings for the limited sample of Australian fin spines. The two alternative growth curves were applied in the assessment uncertainty grid. In each case, the mean of the male and female curve was used as fixed input. Variances on length-at-age were estimated in the overall fitting (from starting values that reflected the combined variance of males and females). Ignoring the sexual dimorphism that is know 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, and are included in Table 2 and Table 3 as part of the combined growth/maturity/mortality assumptions defined in 3.2.9.

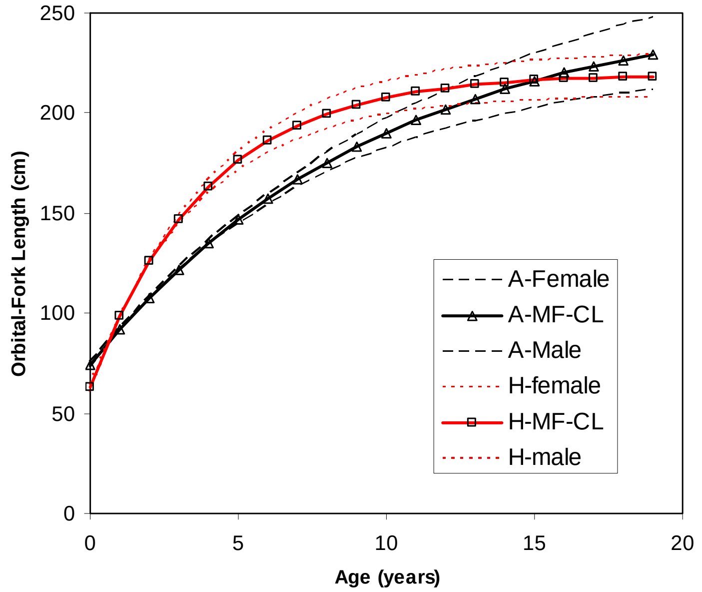


Figure 12. Swordfish growth curves estimated from Australian samples ('A' in the legend) from Young et al. 2008 and Hawai'ian samples ('H') from DeMartini et al (2006). Female (upper) and Male (lower) curves are shown for each, with the mean used in the assessment models (labelled "MF-CL"). Note that the model uses lower jaw fork length data while the figure illustrates the difference in orbital fork-length.

3.2.8 Maturity Schedules

Young et al. 2008 suggest that there are also methodological differences and uncertainties in the interpretation of swordfish maturity-at-size. However, the greatest uncertainty on maturity-at-age is attributable to the uncertainty in age estimation. The maturity assumption adopted in 2006 was derived from Young and Drake 2002. As an alternative maturity schedule assumption, we adopted one of the more extreme maturity interpretations used in other swordfish assessments (age of 50% maturity = 4 years) (Figure 13). These two maturity assumptions were only considered in conjunction with specific growth curves and mortality vectors, and are included in Table 2 and Table 3 as part of the combined growth/maturity/mortality assumptions defined in 3.2.9.

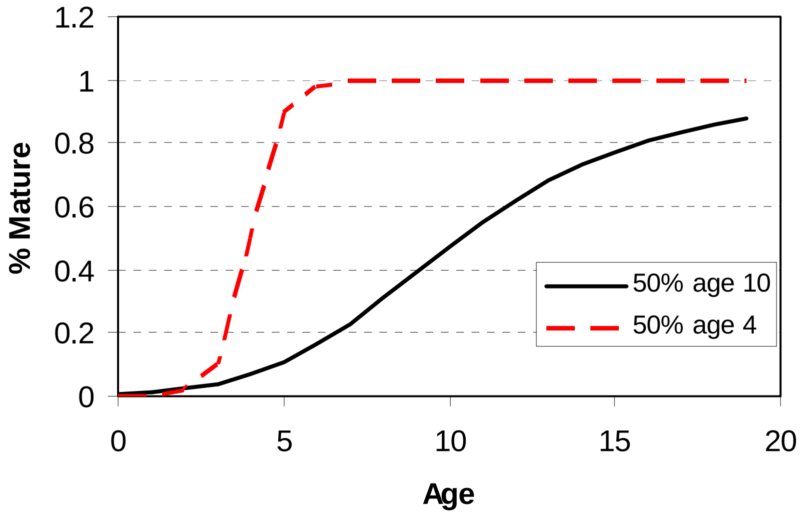


Figure 13. Alternative swordfish (female) maturity schedules assumed in the 2008 assessment. The 50% age 10 curve is taken from Young and Drake (2002); the 50% age 4 curve is qualitatively consistent with assumptions adopted in other assessments in the Atlantic and Eastern Pacific. Only the 50% age 10 value was used in 2006.

3.2.9 Natural Mortality

Given the difficulty in tagging swordfish, and 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 – 05. In this assessment we attempted to span a range of options based on speculation about life history dependent factors.

A total of 8 vectors of *M* by age were examined, 4 corresponding to each of the two growth curve options described above. For each growth curve, two values of mean *M* were derived from Pauly (1980), which describes *M* from a number of species in relation to the k parameter from the von Bertalanffy growth equation, and the species temperature preferences. The temperature preferences used here correspond to the highest and lowest values (14.57, 22.83° C) identified for swordfish in Boyce et al. (2008). Note that the authors identify temperature preferences which have a much narrower range than the temperature tolerances identified in the same paper. This results in mean *M* values for slow growth curves of: 0.16 and 0.2, and for the faster growth curves: 0.31 and 0.38. For each value of mean *M* (mean over ages 1-15 years), two vectors of *M* by age were derived from the following:

$$M_a = 0.1 + (L_{\inf} / L_a)^{K_1} + K_2 \cdot Maturity_a ,$$

where:

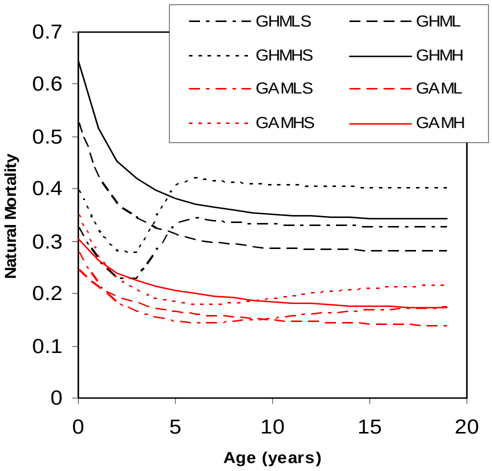
$L_{\inf}$ = von Bertalanffy growth parameter

L_a = mean length-at-age

$Maturity_a$ = proportion mature at age

K_1 , K_2 = somewhat arbitrary constants as indicated below.

This equation is simply intended to represent variation in *M* by age that is biologically plausible given what we know from other species, (e.g. tagging studies and observations of maximum age for Southern Bluefin tuna suggest substantial differences in M by age, Polacheck et al. 1998), and spawning (plus associated migratory activity) is generally a stressful process that might be expected to increase mortality. The magnitude of the curves was arbitrarily bounded with a maximum difference of M between ages of a factor of 1.5 (excluding ages 0 and 16+).



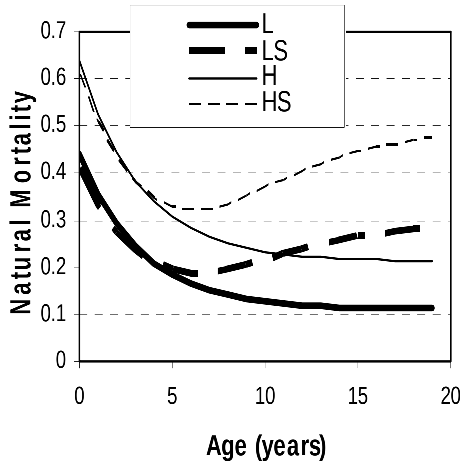


Figure 14. Natural mortality assumptions used in the 2008 assessment (left panel) and 2006 (right panel). Note that the upper 4 (GH) vectors in the left panel were assumed in relation to the faster growth curve, while the lower 4 (GA) vectors were assumed in relation to the slower curve. The *M* vectors assumed in 2006 are shown in the right panel for comparison.

Note that the GH mortality vectors were only assumed in conjunction with the fast growth curves and young age at maturity, while the GA vectors were only assumed in conjunction with the slow growth and older age at maturity. The intent of this large range was to be reasonably confident that realistic values were encompassed by the range explored, and to determine whether the assessment results are sensitive to the growth/maturity/mortality assumptions. In Table 2 and Table 3 these combined assumptions are defined:

- GAMH - Slow growth, 10+ maturity, relatively high *M*
- GAMHS -Slow growth, 10+ maturity, relatively high *M* with spawning effect
- GAML - Slow growth, 10+ maturity, relatively low *M*
- GAMLS - Slow growth, 10+ maturity, relatively low *M* with spawning effect
- GHMH - Fast growth, 4+ maturity, relatively high *M*
- GHMHS - Fast growth, 4+ maturity, relatively high *M* with spawning effect
- GHML - Fast growth, 4+ maturity, relatively low *M*
- GHMLS - Fast growth, 4+ maturity, relatively low *M* with spawning effect

The range of mortality assumptions used in 2006 was similar in magnitude to the range employed this year (mean *M* = 0.16, 0.24, 0.26, 0.41). However, in 2006 only one growth and mortality schedule was considered, and only the L and H mortality options (Figure 14) yielded results that were judged to be plausible.

3.2.10 Migration rates

A range of migration rate assumptions were explored in relation to the analysis of PSAT and conventional tags described in Kolody and Davies (2008). The migration rate estimates were derived from fitting a simple one dimensional diffusion model (with geo-positioning error) to the available PSAT and conventional tags. The estimates of longitudinal mixing were translated into bulk transfer coefficients appropriate to the swordfish assessment structure. Further analyses are expected to be undertaken in relation to the swordfish PSAT tags (Chris Wilcox, CSIRO, pers. comm.), however, given the small number of deployments to date there was not much justification for a more detailed analysis at this time.

In the SWP models, only the approximate upper and lower bounds estimated from the tag analysis were considered:

- D05 – Exchange of ~5% of fish per quarter between areas 1 and 2
- D10 – Exchange of ~10% of fish per quarter between areas 1 and 2

In the combined SWP-SCP models, a much more exploratory position was adopted to see if sensible results could be obtained, including the following range of options:

- D00 – Exchange of 0.1 % of fish per quarter between all adjacent areas
- D10 – Exchange of 10 % of fish per quarter between all adjacent areas
- DF – Migration rates between all adjacent areas were estimated as free parameters (constant with age)

3.2.11 Time period

The models were iterated on a quarterly time-step from 1952-2007. An additional 10 years of projections 2008-2017 were conducted, assuming that catch remained constant at 2007 levels (including the seasonal pattern). In MULTIFAN-CL, projections consist of extending the time series with an assumed future effort (or catch) time series, and the model estimates the missing catch (or effort) that corresponds to the provided values (with deterministic future recruitment driven by the stock recruitment relationship). A similar assumption about proportionate effort by fleet is used in the equilibrium yield (and MSY) calculations.

3.2.12 Age and Sex Structure

The modeled population consisted of 40 quarterly age classes (0-19.75+ in years); both sexes combined. Recruitment (age 0) was assumed to occur annually, in the first quarter.

3.2.13 Catch in Numbers Observation Errors

We assume that the total catches are essentially error free (approximate observation error CV ~ 0.07), although it is likely that some additional fishing-related mortality (e.g. discarding of small fish) has been overlooked. Given the weak size constraints imposed by the model, the predicted total catch in numbers tended to agree almost perfectly with the observations (not shown).

3.2.14 Assessment Model Uncertainty Grids

South-West Pacific

Table 2 summarize the combinations of assumptions in the SWP uncertainty grid. In the SWP, a balanced design of 7 assumption combinations was proposed:

(hxx) X (Dxx) X (Gxx) X (rxx) X (ESxx) X (Uxx) X (Sxx)
= 2 X 2 X 8 X 2 X 2 X 3 X 2 assumptions
= 768 models

The unconstrained selectivity assumption SF tended to estimate non-decreasing selectivity for the southern fleet, so it seemed redundant to retain both the SM and SF assumptions in the uncertainty grid. The SM assumption was dropped, and a total of 384 models were fit.

South-Central Pacific

Table 3 summarize the combinations of assumptions in the SCP uncertainty grid. The SCP assessment was conducted after the SWP assessment, and a different set of assumptions was explored, with increased number of options for migration and recruitment variability, and a reduced number of options for Growth/Maturity/Mortality, catch-at-size down-weighting and selectivity constraints:

(hxx) X (Dxx) X (Gxx) X (RSxx) X (rxx) X (ESxx) X (Uxx) X (Sxx)
= 2 X 3 X 2 X 2 X 2 X 1 X 3 X 1 assumptions
= 144 models

Table 2. Abbreviations and model assumptions used in the SW Pacific model uncertainty grid. The full cross of factors results in a grid of 768 models; removal of the ES20 and SM options resulted in the final grid of 192 models.

Scenario Abbreviation	Definition
Spatial Definition	
A12F11	Areas 1-2 (South-West Pacific), 11 fisheries
Beverton-Holt Stock Recruitment Relationship steepness (h)	
h65	h prior mode = 0.65 (beta prior parameters = 6500, 3500)
h90	h prior mode = 0.90 (beta prior parameters = 9000, 1000)
Migration Rates	
D05	Migration to/from adjacent regions ~ 0.05 per quarter (all ages)
D10	Migration to/from adjacent regions ~ 0.10 per quarter (all ages)
Growth / Maturity / Natural Mortality	
GAMH	Slow growth, 10+ maturity, relatively high M
GAMHS	Slow growth, 10+ maturity, relatively high M with spawning effect
GAML	Slow growth, 10+ maturity, relatively low M
GAMLS	Slow growth, 10+ maturity, relatively low M with spawning effect
GHMH	Fast growth, 4+ maturity, relatively high M
GHMHS	Fast growth, 4+ maturity, relatively high M with spawning effect
GHML	Fast growth, 4+ maturity, relatively low M
GHMLS	Fast growth, 4+ maturity, relatively low M with spawning effect
Recruitment variability	
r1	likelihood term ln(SD) = 0.1
r5	likelihood term ln(SD) = 0.5
Catch-at-Size Likelihood Assumptions	
ES05	input sample size downweighted by factor of 1/5 (1000 maximum)
(ES20*)	input sample size downweighted by factor of 1/20 (1000 maximum)
CPUE Likelihood Assumptions	
UA1	all informative CPUE series weighted with CV ~ 10%
UAJ	Australia/New Zealand CV ~ 10%; Japan CV ~ 25%
UJA	Australia/New Zealand CV ~ 25%; Japan CV ~ 10%
Selectivity Constraints	
SF	all selectivities unconstrained
(SM**)	fishery 8 selectivity non-decreasing; all others unconstrained

* The input effective sample size ES20 model dimension always resulted in very poor fits to some of the size frequency distributions and was removed from the SWP Most Plausible Ensemble (see 4.1.1)

**Partial application of the SM assumption in the uncertainty grid suggested that it was frequently (possibly always) redundant (i.e. the unconstrained selectivity of fishery 8 was estimated to increase with age), and hence this dimension was dropped.

Table 3. Abbreviations and assumptions used in the South-West-South-Central (SWSC) Pacific assessment uncertainty grid of 144 models.

Scenario Abbreviation	Definition
Spatial Definition	
A14F18	Areas 1-4 (South-West and South-Central Pacific), 18 fisheries
Beverton-Holt Stock Recruitment Relationship steepness (h)	
h65	h prior mode = 0.65 (beta prior parameters = 6500, 3500)
h90	h prior mode = 0.90 (beta prior parameters = 9000, 1000)
Migration Rates	
D00	Migration to/from adjacent regions ~ 0.0001 per quarter (all ages)
D10	Migration to/from adjacent regions ~ 0.10 per quarter (all ages)
DF	Migration to/from adjacent regions estimated (variable with age)
Growth / Maturity / Natural Mortality	
GAML	Slow growth, 10+ maturity, relatively low M
GHMHS	Fast growth, 4+ maturity, relatively high M with spawning effect
Recruitment Spatial Distribution	
RS1	Recruitment is split evenly among areas
RS2	Recruitment distribution is split among areas is estimated, constant over time
Recruitment variability	
r1	likelihood term ln(SD) = 0.1
r5	likelihood term ln(SD) = 0.5
Catch-at-Size Likelihood Assumptions	
ES05	input sample size downweighted by factor of 1/5 (1000 max)
CPUE Likelihood Assumptions	
UA1	all informative CPUE series weighted with CV ~ 10%
UAJ	Australia/New Zealand CV ~ 10%; Japan CV ~ 25%
UJA	Australia/New Zealand CV ~ 25%; Japan CV ~ 10%
Selectivity Constraints	
SF	all selectivities unconstrained

4 Results and Discussion

Several hundred models were fit in the course of this assessment. The MULTIFAN-CL software converged successfully in all cases (i.e. very small final gradients attained). While we cannot be certain that global minima were always identified, there was fairly consistent behaviour among models, and no evidence of predictions that were grossly unexpected given the model specifications (at least for the SWP results which were examined in much greater detail than the combined SWP-SCP results). Results and discussion are separated for the two assessments in the following.

4.1 South-West Pacific Assessment

The following sections present: i) a brief description of the model selection process, in which the Most Plausible Ensemble of models was defined from the SWP uncertainty grid, ii) a detailed review of two models with stock status estimates at the extreme optimistic and pessimistic ends of the distribution (defined by MSY), iii) a stock status summary of results from the Most Plausible Ensemble of models, iv) a comparison of the relative importance of model selection uncertainty and parameter estimation uncertainty in the assessment and v) A comparison between stock status estimates from the 2006 and 2008 assessments.

4.1.1 Defining plausible models from the SWP uncertainty grid

There is always an element of subjectivity in the formulation and selection of models, and different analysts will have different priorities with respect to what they consider most important. While theoretical statistical measures (e.g. AIC, BIC) can provide some guidance in the model selection process, these measures should be used cautiously when statistical assumptions are known to be violated. Furthermore, these indices are not applicable when fundamental characteristics of models differ (e.g. different data are included in the model, or sample sizes are manipulated to account for non-random sampling). By using the model selection process defined below, we do not resolve the need to make arbitrary decisions or guarantee that the best decisions are made. However we would argue that it is useful to explicitly define plausibility criteria because 1) they allow a large number of models to be compared rapidly and consistently, and 2) the selection criteria are openly available for criticism and debate. As in 2006, we focused on three initial diagnostics:

1) We describe the quality of fit to the CPUE series on the basis of the degree of agreement between predictions and observations (i.e. independent of the assumed variance of the effort deviations) using the Root Mean-Squared Error. For fishery *f*:

$$RMSE_f = \sqrt{\tfrac{1}{N}\sum \left(\ln(CPUE_f^{predicted} / CPUE_f^{observed})\right)^2}$$

It is usually the case in these models that CPUE RMSE increases due to a systematic lack of fit in the form of a temporal trend in residuals (as opposed to random noise). While we are probably most interested in the systematic lack of fit, the two are usually strongly positively correlated (although this might not be true if there is a seasonal component for the CPUE variability that is poorly described).

2) To compare the quality of fit between predicted and observed size frequency distributions, we use the Effective Sample Size (ESS), which is independent of the assumed sample sizes (and catch-at-size likelihood term) in the assessment model objective function (McAllister and Ianelli 1997). For fishery f, the ESS is defined:

$$ESS_f = \frac{1}{T}\sum_{t}^{T}\left(\frac{\sum_{l} p_{f,t,l}(1-p_{f,t,l})}{\sum_{l}(o_{f,t,l}-p_{f,t,l})^2}\right),$$

where:

$p_{f,t,l}$ = proportion of predicted catch in size bin *l* at time t in fishery f, and

$o_{f,t,l}$ = proportion of observed catch in size bin *l* at time t in fishery f.

This value can be interpreted as the truly random sample size that would on average yield a quality of fit between predictions and observations as that which resulted. Note the unfortunate confounding of terms, in that "effective sample size" is also the term used to describe the manipulation of assumed sample sizes for size frequency likelihoods. We use "input ES" to refer to model input assumptions, and "output ESS" to refer to model output diagnostics.

3) In 2006, it was observed that the ESS was not very useful for fisheries with very small sample sizes. Sometimes vastly different fishery selectivities could be estimated which resulted in very similar output ESS diagnostics. However, large differences were apparent between predicted and observed mean sizes that were strongly indicative of a model problem (e.g. we are very confident that the New Zealand charter fleet catches predominantly very large fish, and would not consider model results plausible if this effect is not captured by the model). Hence the mean size bias for fishery *f* was used as third model diagnostic:

$$meanSizeBias_f = \tfrac{1}{T}\sum_{t=1}^{T}(\overline{L}_t^{\Pr edicted} - \overline{L}_t^{Observed}).$$

Note that residuals cancel out in this index (but should be captured in the ESS index), as this index is intended to describe major biases.

The relationship between the quality of fit diagnostics and the various assumptions in the SWP uncertainty grid are illustrated in Figure 15-Figure 17. Figure 15 illustrates that the fit to the Australian fishery (4) CPUE is most sensitive to the CPUE weighting assumption. Not surprisingly, down-weighting the fit to the Australian CPUE relative to the Japanese CPUE reduces the CPUE RMSE for the Australian series somewhat (i.e. assumption UJA vs: UA1 or UAJ). Figure 16 illustrates that the quality of fit to the Australian size composition data (measured by the output ESS) is greatly decreased by down-weighting the assumed effective sample sizes (input ES assumption ES5 vs: ES20). Figure 17 illustrates that the catch-at-size distributions are badly biased for at least one of the fleets with the ES20 assumption, especially when combined with the slow growth curve (GA) assumptions.

On the basis of these plots, it was decided to remove all of the ES20 assumptions from the model uncertainty grid. The sources of the variance in quality of fit diagnostics associated with the other assumptions in the uncertainty grid are less severe, and do not seem to provide any obvious justification for reducing the grid further.

Table 1 compares model diagnostics for the SWP uncertainty grid for all models with the ES20 assumption and all models without the ES20 assumption. The latter combination of models is hereafter referred to as the Most Plausible Ensemble (MPE).

In the 2006 assessment there were a number of additional implausible results identified for individual models that did not detract from a high quality fit to the data. In particular, some formulations estimated dubiously large spawning biomass or very high exploitation rates in the southern (SBT-targeting) region. These problems were not observed with the revised spatial structure adopted in 2008. However, the selectivity of fisheries 3 and 11 (Japanese Area 1 South and New Zealand domestic) were suspicious in that they tended to be bimodal to some extent (see section 4.1.2). This might be credible for the southern Japanese fishery (3), as it is difficult to properly partition the northern (primarily yellowfin/bigeye-targeting) and southern (SBT-targeting) fleets. One can speculate about the plausibility of the bimodal New Zealand domestic fleet selectivity, however given that it was almost ubiquitous and identified late in the process, no attempt was made to explore the issue further.

It was notably unexpected that the 8 growth/maturity /mortality assumptions all seemed to have rather similar outcomes in terms of the quality of the model fits to the data, although the fast growth options seem to be somewhat better in the MPE (Figure 18). This is probably the result of i) the relatively poor size sampling data for most fleets, and ii) the lack of clearly defined modes in the catch composition (possibly exacerbated by sex dimorphism and size/sex-dependent seasonal migrations within fisheries). There is obviously a lot of flexibility for the models to trade-off growth and natural mortality and fishery selectivity, and we would not expect the model to be able to reliably estimate growth and mortality in this fishery. This emphasizes the need to explore the full range of this biological uncertainty in the assessment.

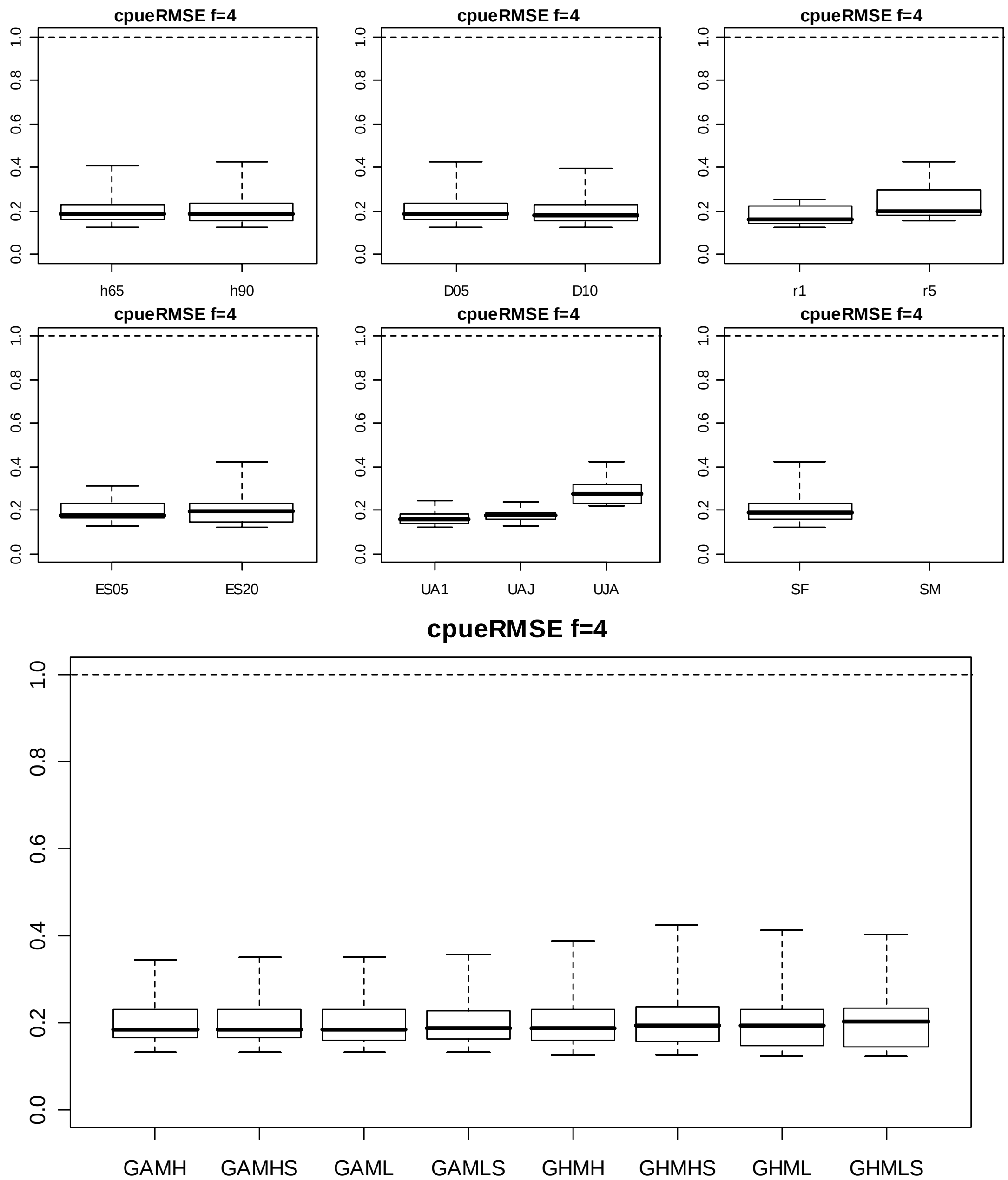


Figure 15. Illustration of how the various assumptions in the uncertainty grid (Table 2) affect the MPD model fit to the Australian longline fishery (fishery 4) CPUE. Y-axis is the RMSE. Each panel contains results from 384 models, partitioned according to individual model factors from the uncertainty grid (boxplots indicate 0, 25, 50, 75 and 100 percentiles).

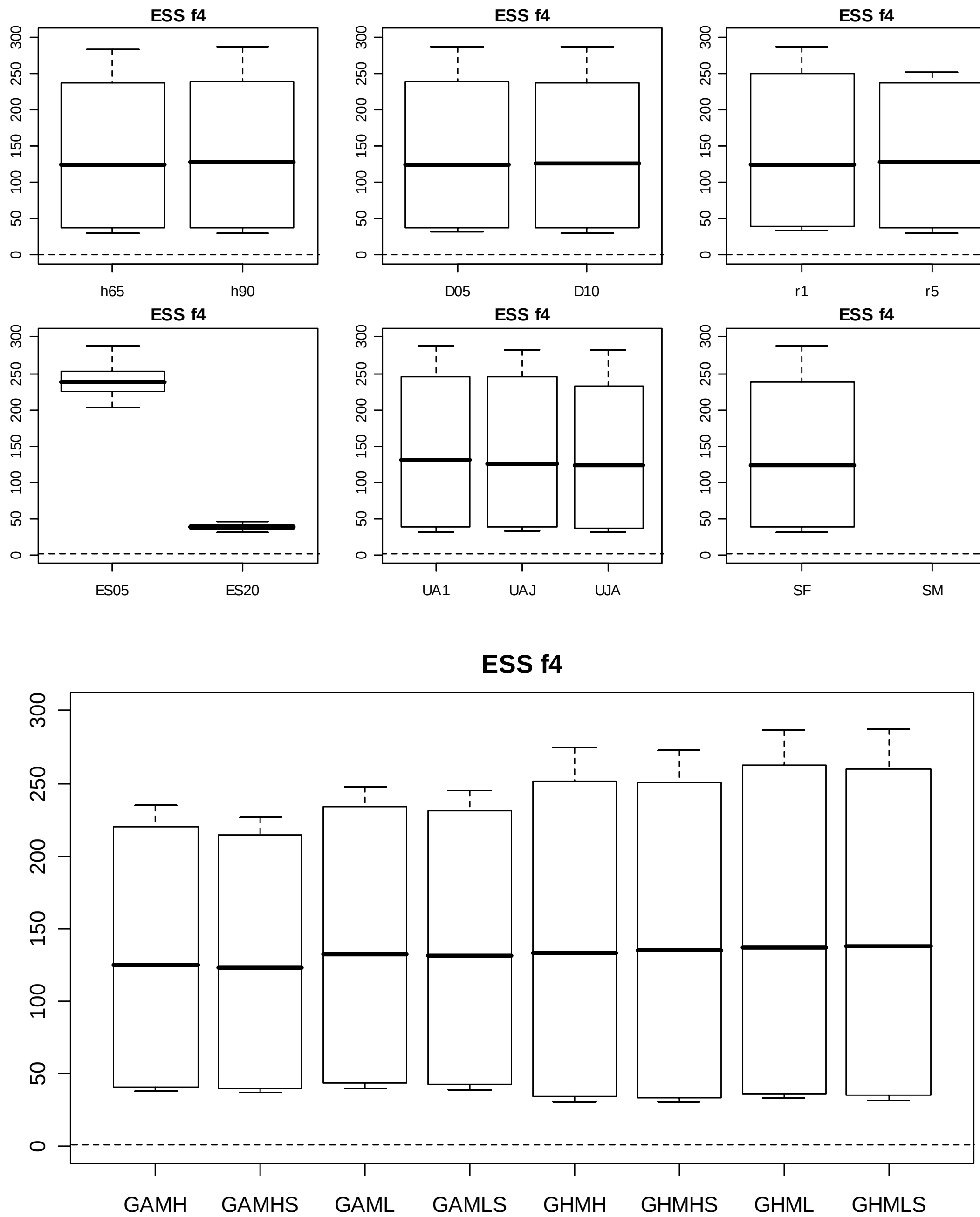


Figure 16. Illustration of how the various assumptions in the uncertainty grid (Table 2) affect the quality of fit to the Australian (fishery 4) size composition data. Y-axis is the mean ESS (see text). Each panel contains results from 384 models, partitioned according to individual model factors from the uncertainty grid (boxplots indicate 0, 25, 50, 75 and 100 percentiles).

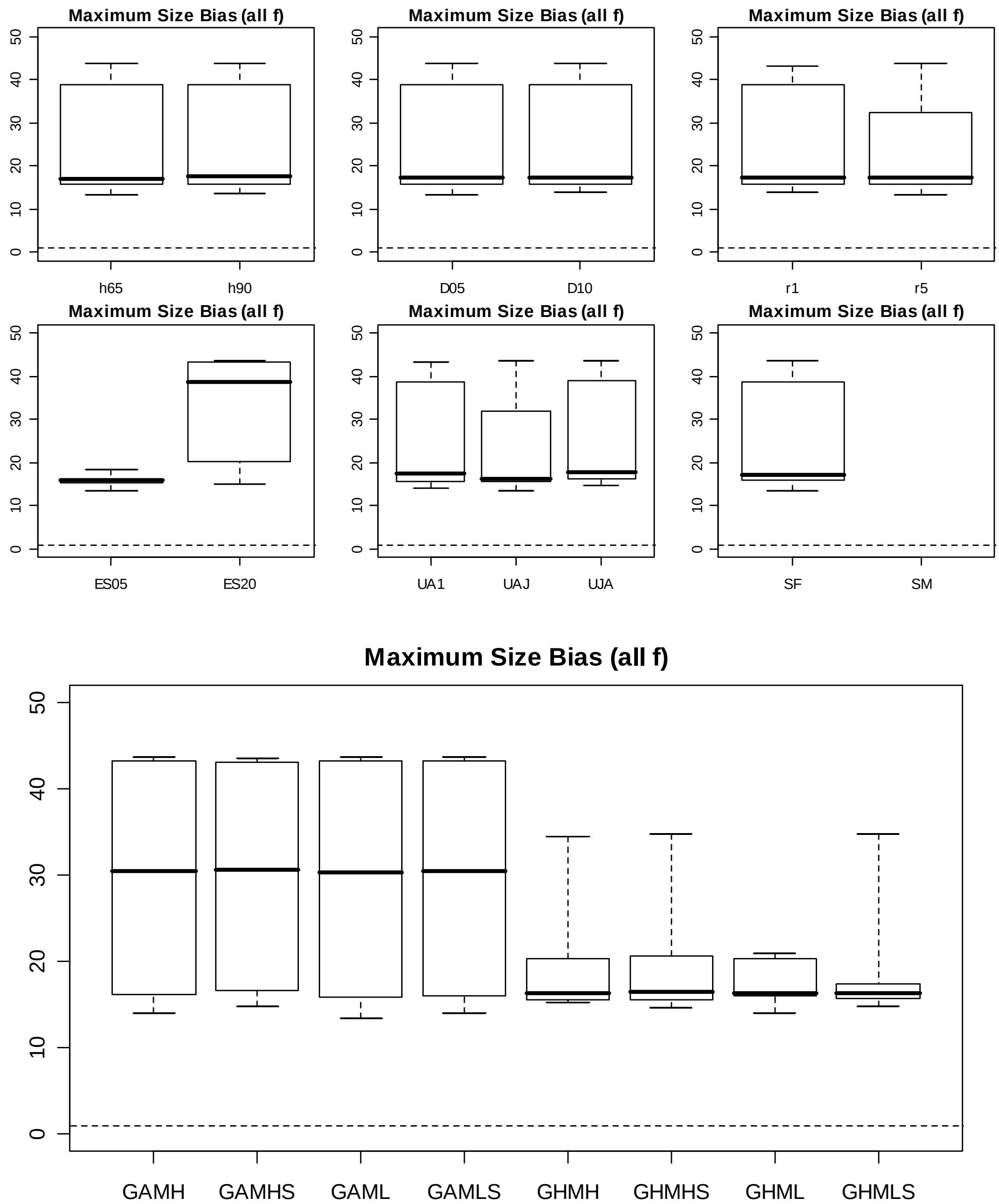


Figure 17. Illustration of how the various assumptions in the uncertainty grid (Table 2) affect the MPD model fit to the size composition data. Y-axis is the maximum of the mean size bias among fleets in cm (excluding the Australian fleet). Each panel contains results from all 384 models, partitioned according to individual model factors from the uncertainty grid (boxplots indicate 0, 25, 50, 75 and 100 percentiles).

Table 4. Summary of model plausibility diagnostics (terms defined in text). The highlighted values indicate major discrepancies between the accepted (ES05) and discarded (ES20) elements of the model assumption grid.

	Uncertainty Grid Specification 192 models **without** ES20 assumption (Most Plausible Ensemble)		192 models **with** ES20 assumption (Rejected)	
Model fit Diagnostic	min	max	min	max
output ESS f=1	18	21	13	14
output ESS f=2	50	58	27	32
output ESS f=3	8	17	3	5
output ESS f=4	203	287	31	46
output ESS f=5	30	35	23	27
output ESS f=6	5	5	4	4
output ESS f=7	41	55	19	25
output ESS f=8	15	37	5	17
output ESS f=9	20	23	10	13
output ESS f=10	15	16	10	12
output ESS f=11	52	67	24	41
maximum size bias f=all	13	19	15	44
cpueRMSE f=2	0.44	0.65	0.39	0.62
cpueRMSE f=4	0.13	0.32	0.12	0.43
cpueRMSE f=7	0.58	0.69	0.55	0.69
cpueRMSE f=11	0.22	0.38	0.22	0.45

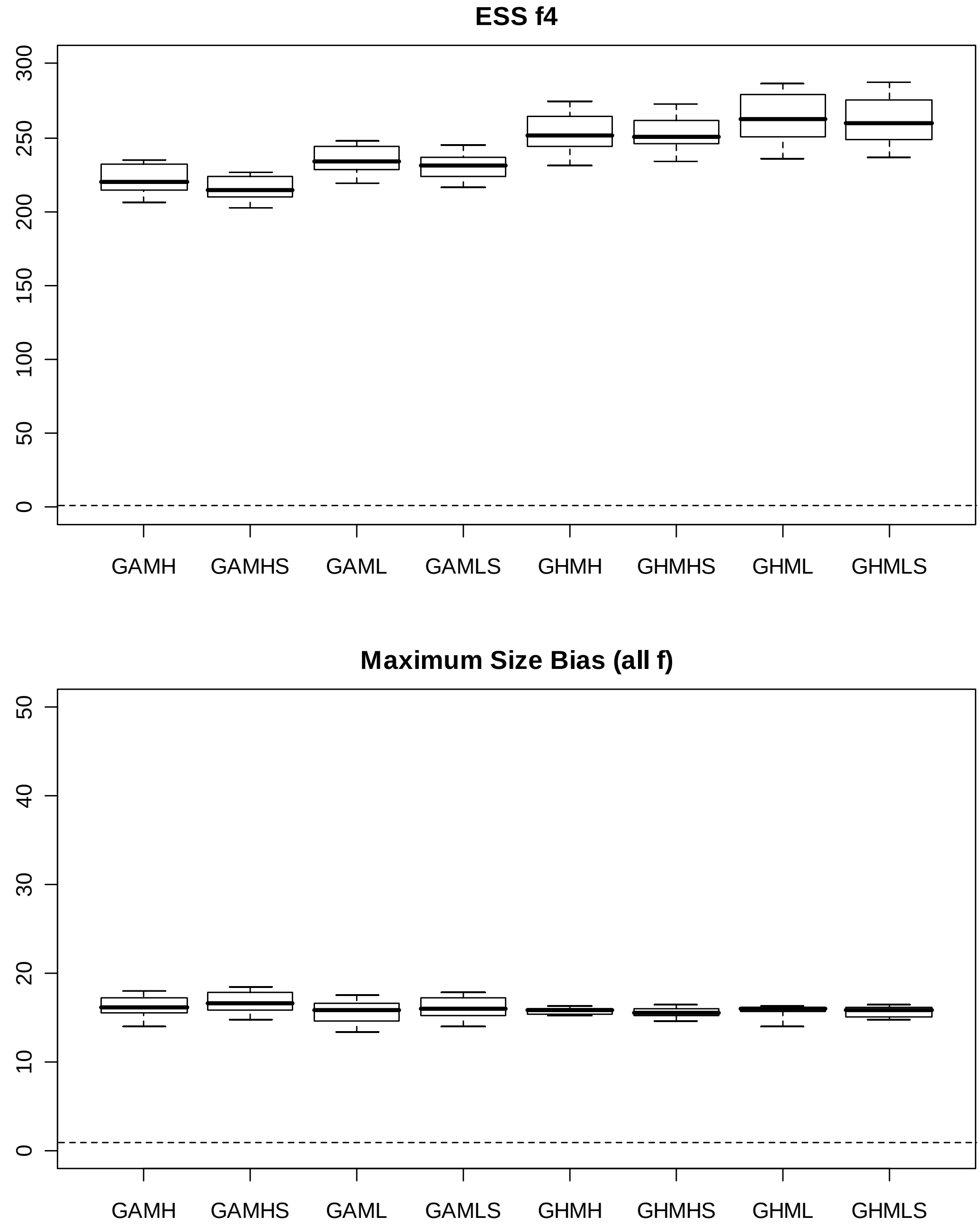


Figure 18. Quality of fit diagnostics for the size composition data, illustrating that the growth/maturity/mortality assumptions did not have a major impact. Each panel contains results from all 192 models in the Most Plausible Ensemble, partitioned according to individual model assumptions (Table 2) from the uncertainty grid (boxplots indicate 0, 25, 50, 75 and 100 percentiles).

4.1.2 Detailed results from two example models

In this section, the MPD results from two example models from the SWP MPE are described in detail. The two models represent the most pessimistic and optimistic results in terms of estimated MSY. The models with the highest and lowest MSY estimates have few overlapping structural assumptions and in many respects we would expect the other model combinations to be intermediate in character between these two.

The MPD fits for the CPUE data are shown over time in Figure 19 and Figure 21. Figure 20 and Figure 22 are scatterplots of the predicted and observed CPUE. Both models seem to describe the general downward CPUE trend since 1998 very effectively for all fleets, and the recent upward trend in the Australian and New Zealand fleets. The Japanese CPUE series are not fit as well as the Australian and New Zealand series, although to some extent this appears to be related to noise in the seasonal variability rather than the inter-annual variability which we are most interested in. For the Japanese fleet in area 2 (fishery 7), there is evidence for a systematic lack of fit for both models (predictions exceed observations in the early 1970s and 2000s; observations exceed predictions in the late 1990s). These results are qualitatively consistent with our relative levels of confidence in the CPUE series from the different fleets, and there does not seem to be a compelling argument to prefer one model over the other on the basis of the CPUE fits.

Figure 23 and Figure 24 illustrate predicted and observed catch size frequency distributions for the two models by fishery, aggregated over time. These plots suggest that the general characteristics of the size composition are reasonably well predicted by both models. The polymodal observed size frequency distributions of some fleets indicate the influence of very small sample sizes (i.e. in the time-averaged plots, frequency distributions were weighted equally among years even though sample sizes differed). The fit appears to be the worst for fisheries 3 and 8, which to some extent reflects the fact that these fisheries are poorly sampled, and might reflect combined characteristics of northern and southern (SBT-targeting) fleets. Qualitatively, it would be difficult to conclude that either the pessimistic or optimistic model was preferable on the basis of these results.

Figure 25 and Figure 26 compare the time series of predicted and observed mean catch-at-size for all fleets. The highly sampled Australian fleet shows a clear declining size trend over time, which is reasonably well described by both models. The other fleets show an erratic pattern of observed mean sizes which again is presumably attributable to poor sampling. Given the poor size composition data, it is not obvious that there are major biases in predicted mean catch sizes for either model.

Fishery selectivities for the pessimistic and optimistic models are shown in Figure 27. The selectivity for the bulk of the fleets (fisheries 1,2,4-7,9 and 10) are strongly dome-shaped. The SBT-targeting fishery (8) shows an increasing logistic shape in both cases (though the optimistic model is slightly domed). Selectivity of fishery 3 in both cases shows a strong mode around age 3-4, but also a second mode on older ages. This might reflect the mixed character of this southern fishery (i.e. sometimes SBT-targeting). It would be preferable if the northern and southern fleets could be more reliably separated, but given the small magnitude of catches in this fishery, it probably does not have much influence on the assessment overall. Of more concern is the selectivity of the NZ domestic fishery (11), which was consistently estimated to be (at least somewhat) bimodal, with modes around age 2-3 and 6-10. We are not aware of any biological justification for the bimodal New Zealand selectivity, though it might be worth investigating the evidence for seasonally variable selectivity and sexual dimorphism. In the current assessment, recognizing the bimodality does not help to distinguish between plausible and implausible models because it was present to a greater or lesser degree in most (or all) models. The variability in selectivity between models would be expected to allow different growth rate and M assumptions to result in similar predicted size composition.

Figure 28 illustrates the fit to the stock recruitment curve for the pessimistic and optimistic models, and suggests that these data do not provide strong evidence to distinguish between the two steepness options examined.

Figure 29 illustrates total and spawning biomass time series estimated from the two example models, in relation to the biomass estimated to have resulted if there had not been any fishing. These plots are useful for examining fishery impacts over time when biomass is believed to be changing substantially for reasons other than fishery exploitation (e.g. recruitment regime shifts). Both of these models attribute part of the biomass decline since 1999 to recruitment declines (but this is clearly more of a concern for the optimistic model). The majority (but not all) of the models attributed at least some portion of the 1997-2004 biomass decline to declining recruitment. This may represent a real effect of recruitment variability, but in some models, at least part of the apparent recruitment shift is an artefact of the model assumptions (e.g. incorrect M specification).

Quality of fit diagnostics and stock status reference points associated with these individual models are listed in Table 5.

Note that predicted and observed total catch in numbers showed no substantial deviations (not shown).

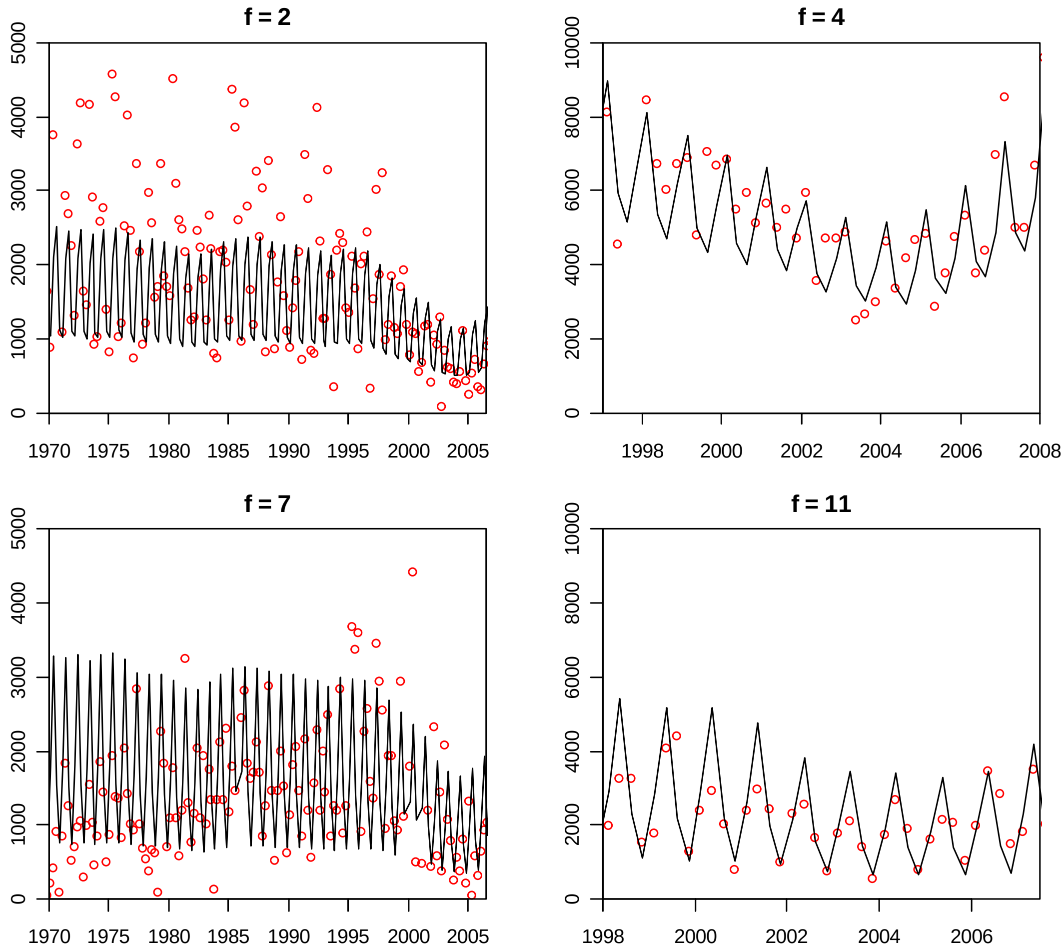


Figure 19. Predicted (lines) and observed (circles) CPUE for the most pessimistic (in terms of MSY) of the Most Plausible Ensemble of 192 SWP models. Only the 4 fisheries that are assumed to have informative CPUE series are shown.

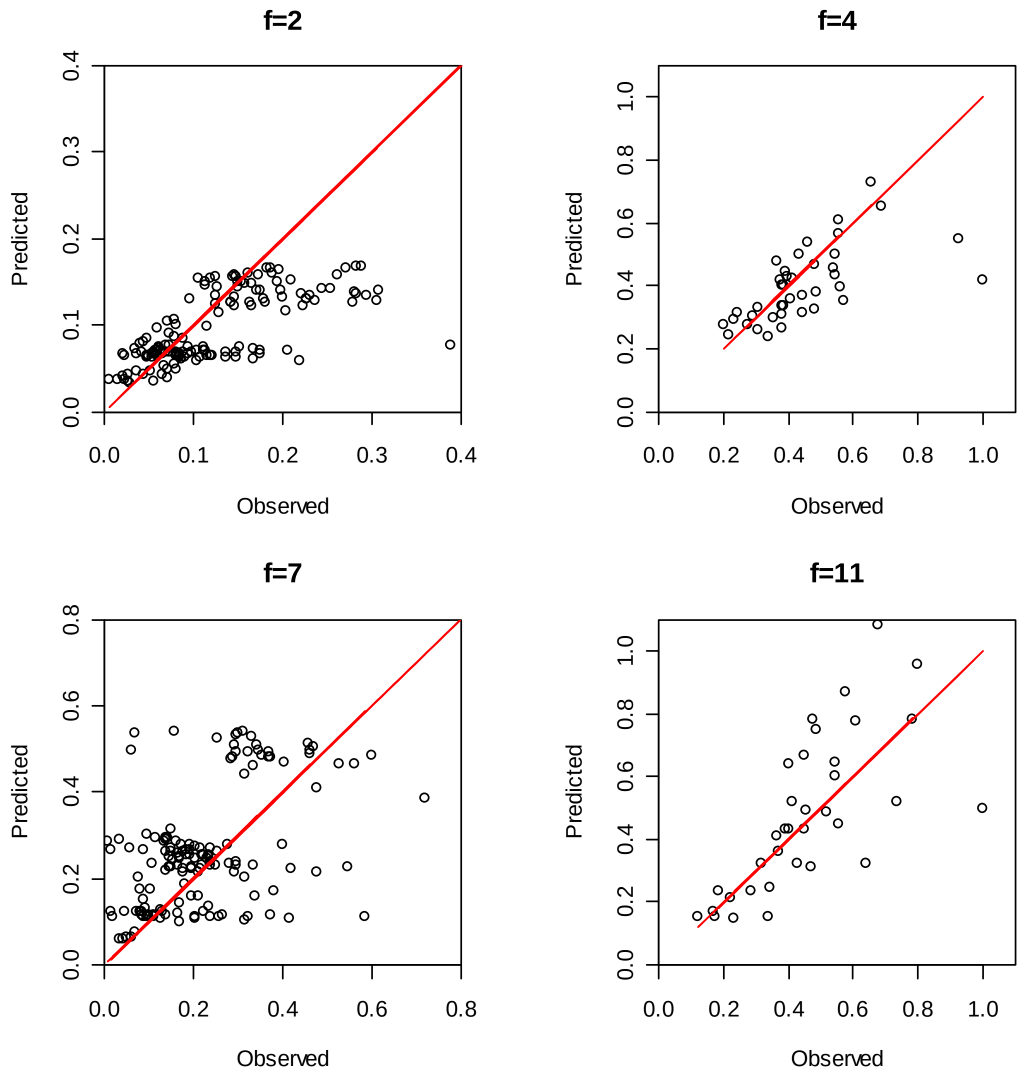


Figure 20. Scatterplot of predicted and observed CPUE for the most pessimistic (in terms of MSY) of the Most Plausible Ensemble of 192 SWP models. Only the 4 fisheries that are assumed to have informative CPUE series are shown. Scale is relative to observed. Lines indicate the 1:1 line). One outlier is off the scale for fishery 2, and two for fishery 7.

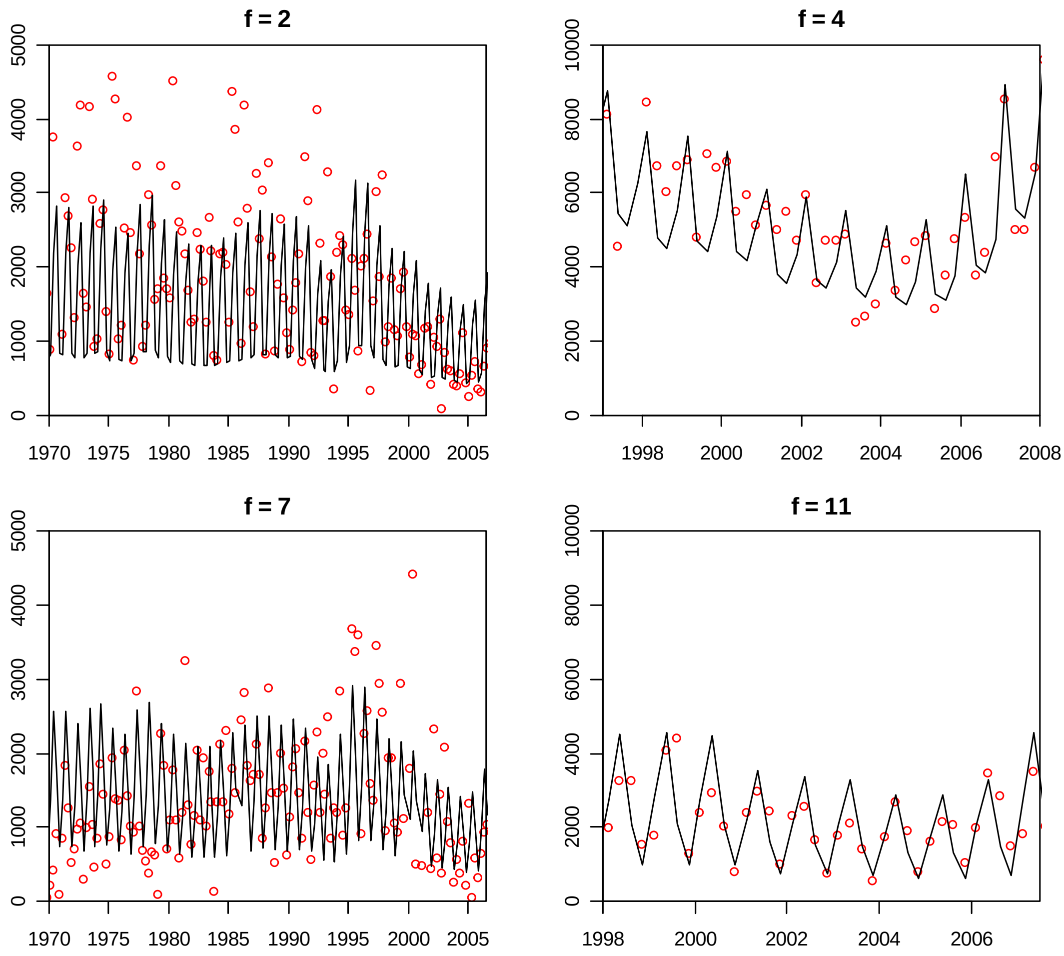


Figure 21. Predicted (lines) and observed (circles) CPUE for the most optimistic (in terms of MSY) of the Most Plausible Ensemble of 192 SWP models. Only the 4 fisheries that are assumed to have informative CPUE series are shown.

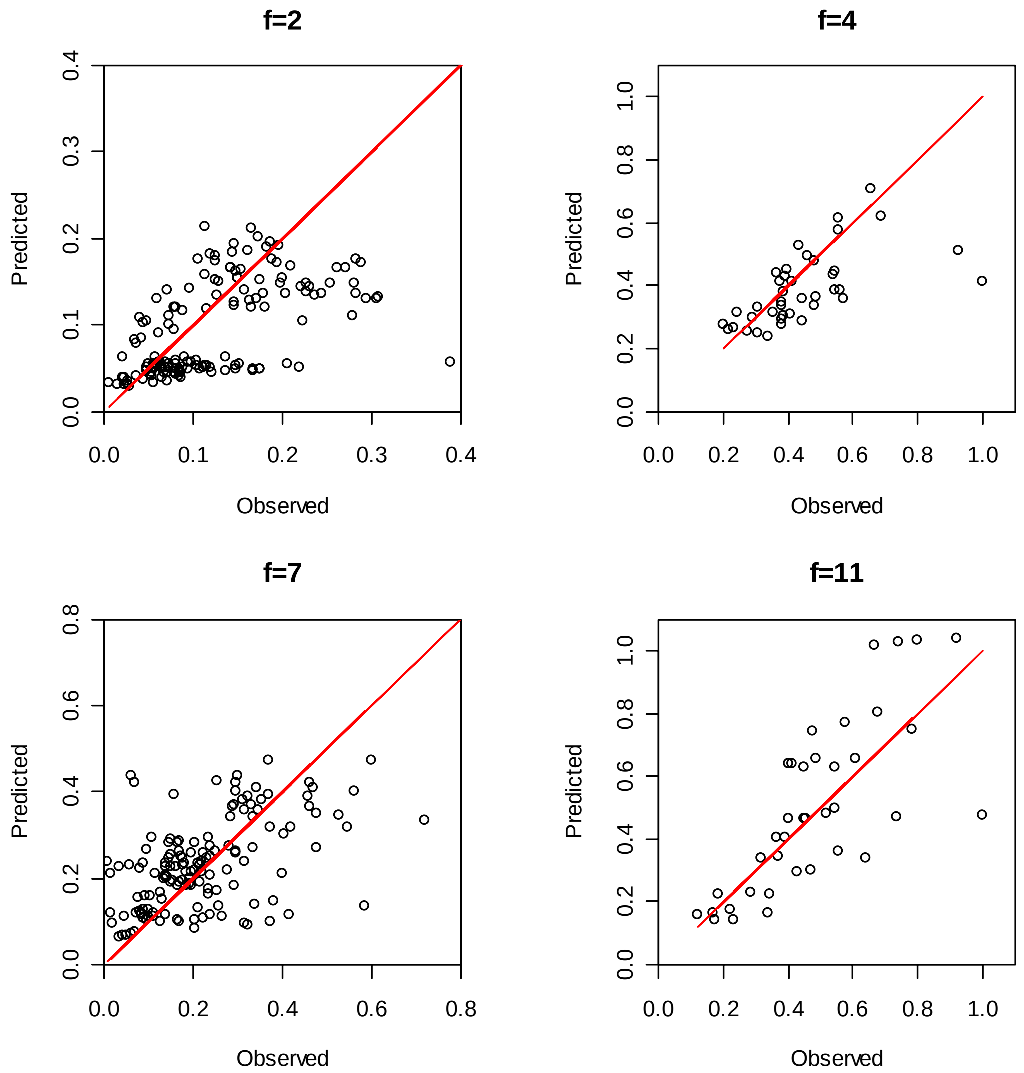


Figure 22. Scatterplot of predicted and observed CPUE for the most optimistic (in terms of MSY) of the Most Plausible Ensemble of 192 SWP models. Only the 4 fisheries that are assumed to have informative CPUE series are shown. Scale is relative to observed. Lines indicate the 1:1 line). One outlier is off the scale for fishery 2, and two for fishery 7.

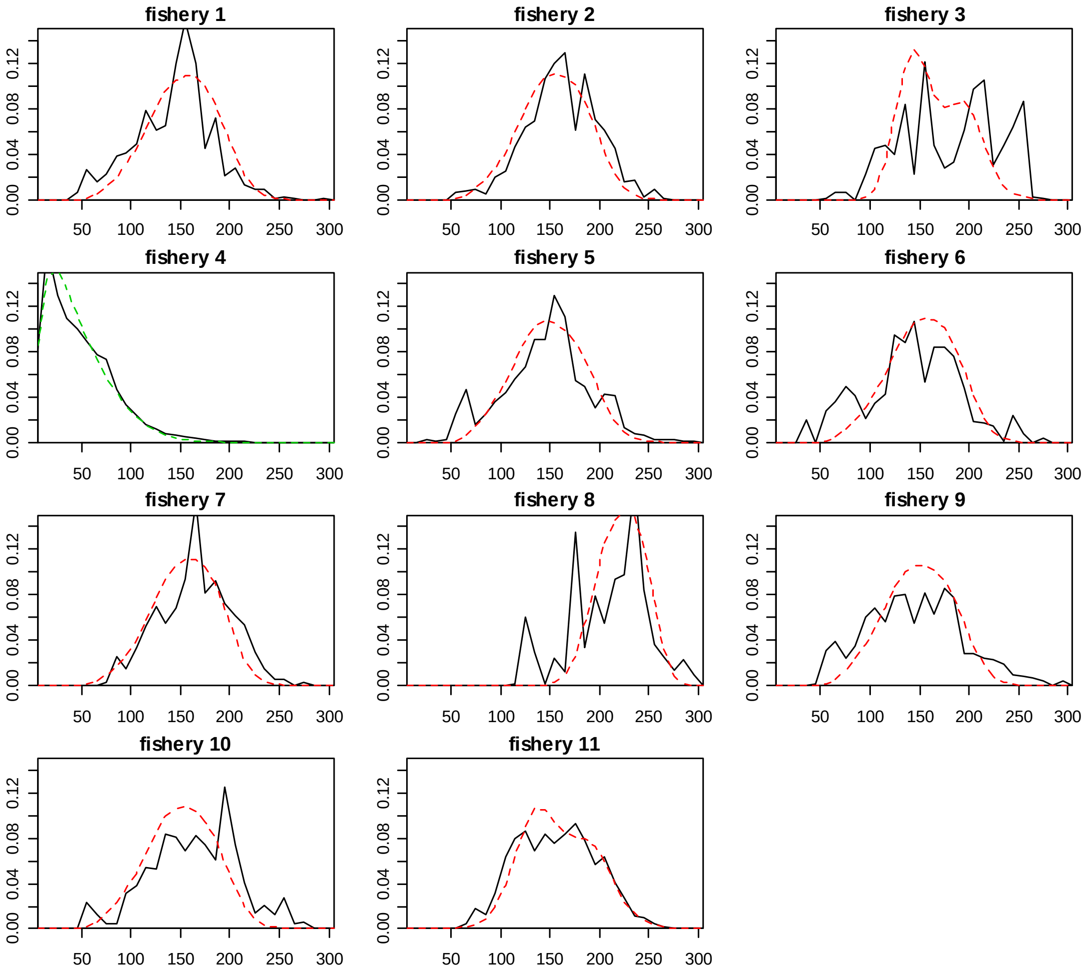


Figure 23. Predicted (broken lines) and observed (solid lines) size frequency distributions aggregated over time for the most pessimistic (in terms of MSY) of the Most Plausible Ensemble of 192 SWP models. Fishery 4 (Australian) is in units of trunked mass (kg), all others are lower jaw fork length (cm).

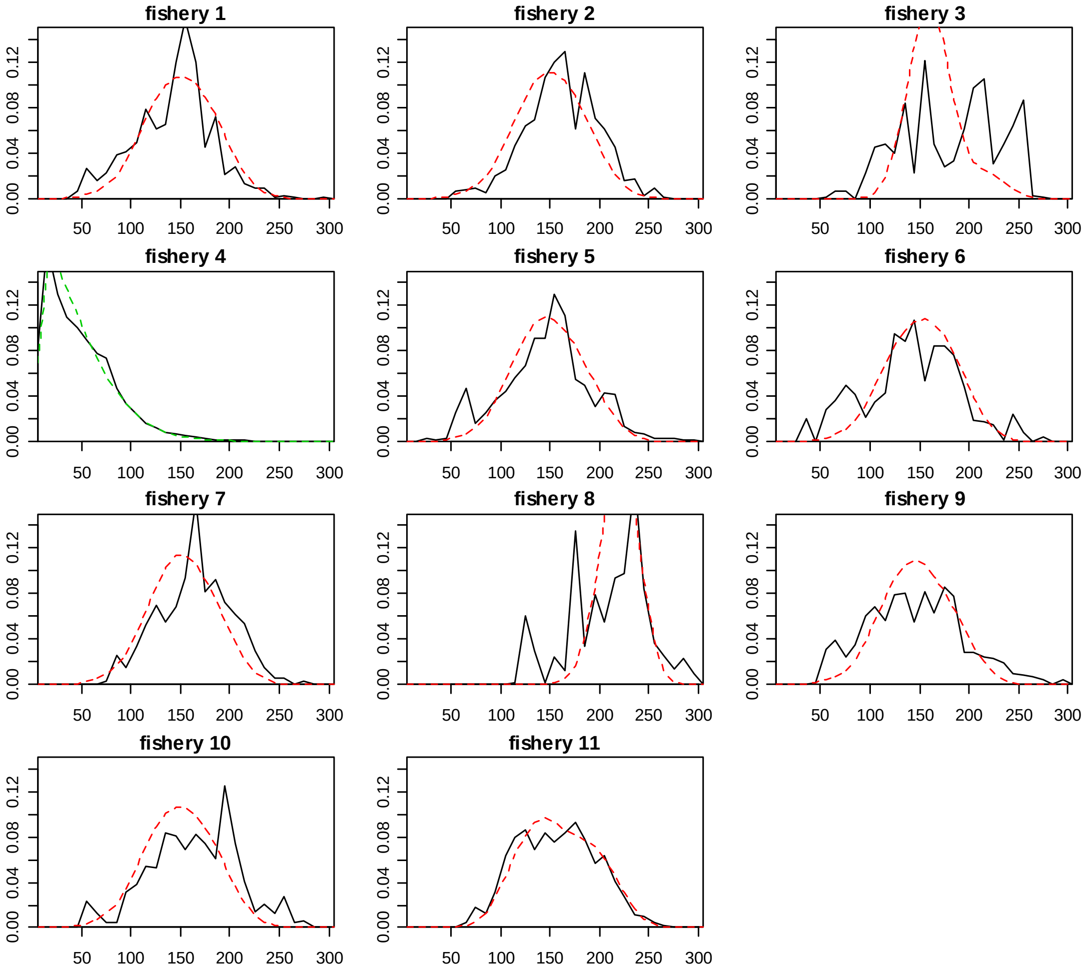


Figure 24. Predicted (broken lines) and observed (solid lines) size frequency distributions aggregated over time for the most optimistic (in terms of MSY) of the Most Plausible Ensemble of 192 SWP models. Fishery 4 (Australian) is in units of trunked mass (kg), all others are lower jaw fork length (cm).

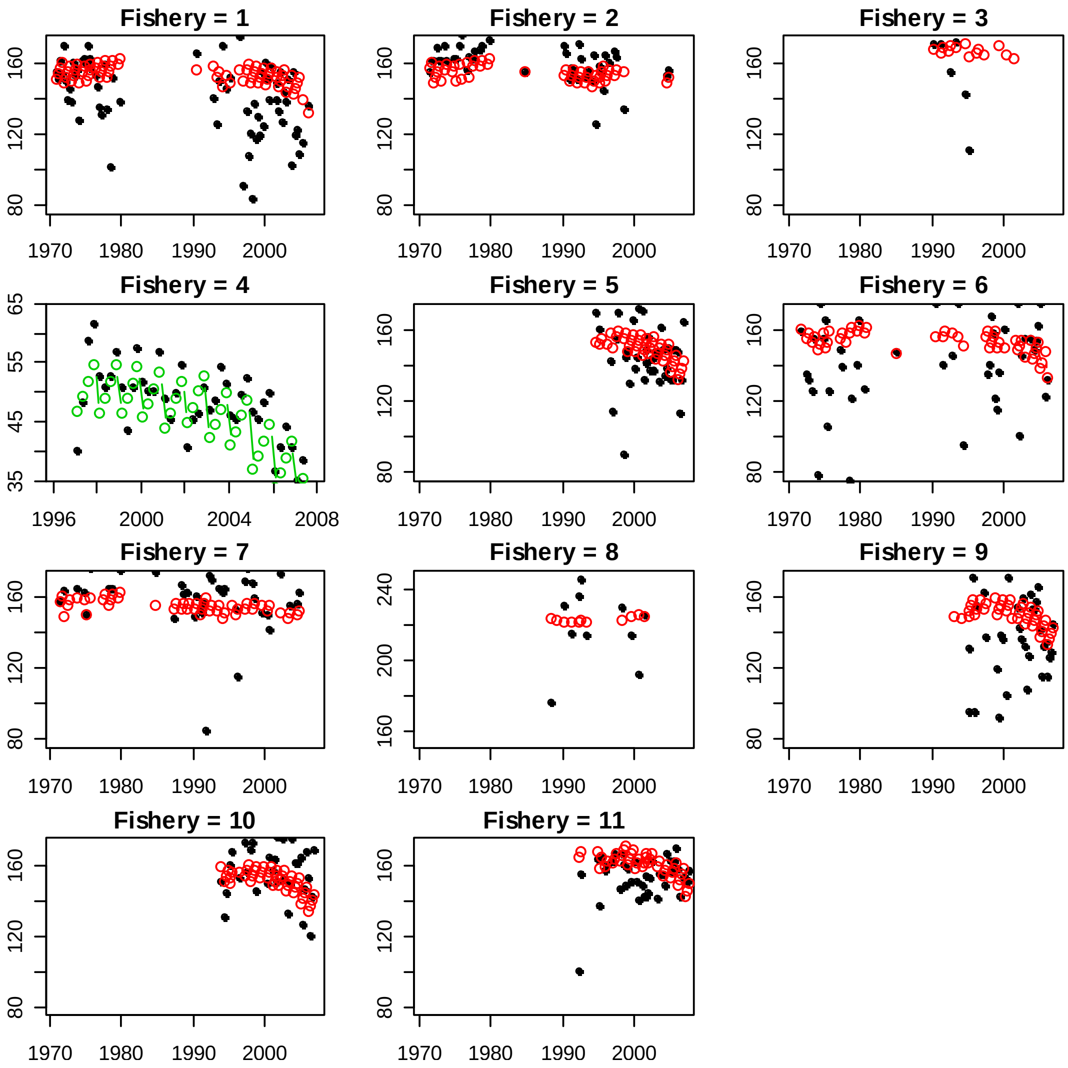


Figure 25. Predicted (coloured circles) and observed (black dots) mean size over time for the most pessimistic (in terms of MSY) of the Most Plausible Ensemble of 192 SWP models. Fishery 4 (Australian) is in units of trunked mass (kg), all others are lower jaw fork length (cm).

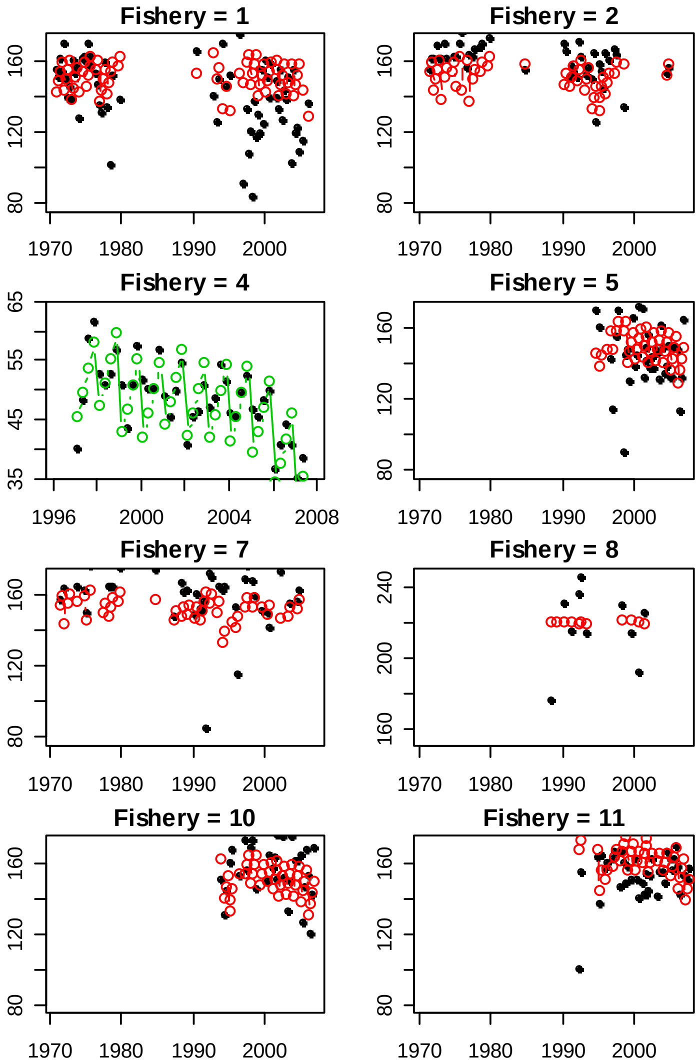


Figure 26. Predicted (coloured circles) and observed (black dots) mean size over time for the most optimistic (in terms of MSY) of the Most Plausible Ensemble of 192 SWP models. Fishery 4 (Australian) is in units of trunked mass (kg), all others are lower jaw fork length (cm).

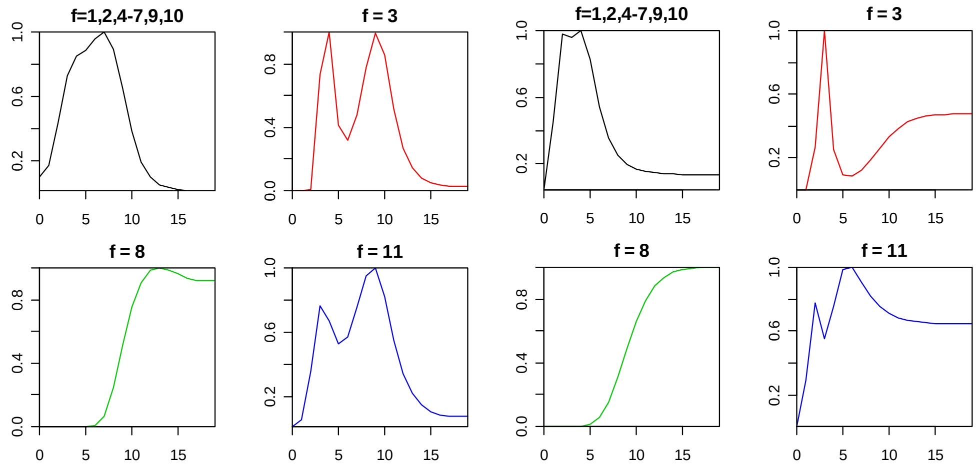


Figure 27. Fishery selectivity estimates from the pessimistic (left 4 panels) and optimistic (right 4 panels) example models. Fisheries are defined in

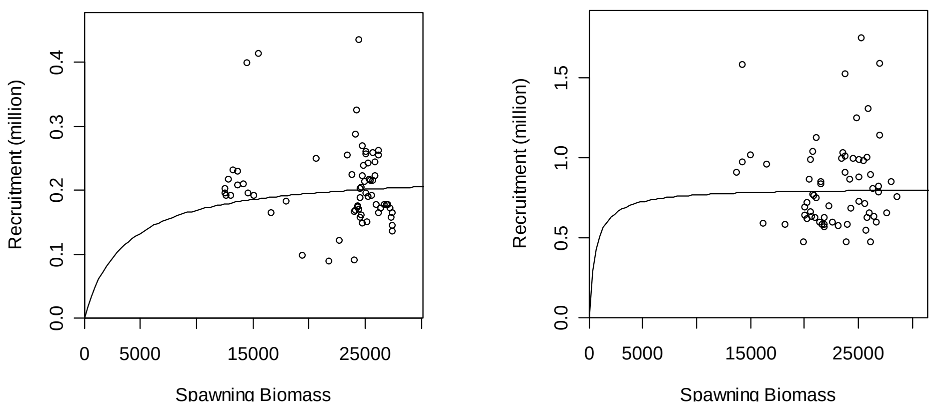


Figure 28. Estimated stock-recruitment relationships for the pessimistic (left panel) and optimistic (right panel) example models.

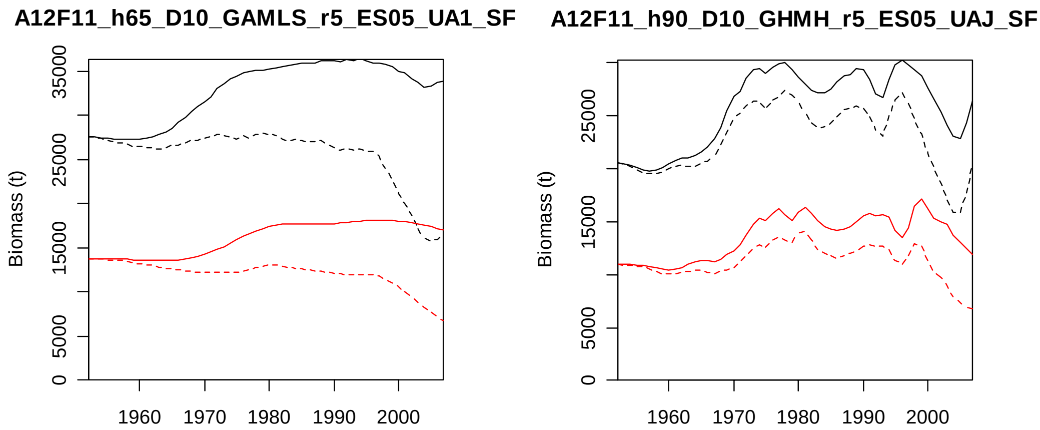


Figure 29. Estimated total (upper black) and spawning stock (lower red) biomass trends estimated for the SWP swordfish population (broken lines) compared to what was estimated would have been observed without fishing (solid lines) for the pessimistic (left panel) and optimistic (right panel) example models.

4.1.3 SW Pacific Stock Status Summary

The preceding section illustrates that even the most extreme models (in terms of MSY) seem to be plausibly consistent with the data and our prior expectations. There may be individual models that are identifiable as slightly more or less agreeable, but the differences do not seem to be as important as in 2006 because the stock status estimates are much more consistent than in 2006. range of results is much more consistent among models than was observed in 2006. If the extremes of the model range are plausible, then it is likely that plausible specifications exist that span the range, and we consider all of the models in the 192 model set to be worth including in the stock status summary.

Table 5 summarizes the MPE goodness of fit diagnostics and MPD estimates for the set of reference points identified at the April workshop (Anon. 2008). Figure 30-Figure 41 partition the reference points according to the individual assumptions from the uncertainty grid. These figures potentially allow one to identify the most important model sensitivities and the highest priorities for research to reduce uncertainties. However, they are not very effective for partitioning effects due to interactions. On the basis of these plots, we note:

- The steepness assumptions had predictable outcomes for MSY-related quantities, i.e. on average, higher steepness corresponds to higher MSY, higher B(2007)/B(MSY) and lower F(2007)/FMSY). However lower steepness was associated with slightly higher estimates of B(2007)/B(1997) and B(2007)/B(unfished) (where B is total or spawning).
- The different diffusion assumptions did not have a noticeable impact on any of the stock status reference points.
- The different assumptions about recruitment variability had little effect on current stock status estimates, but a noticeable effect on projections. The R5 assumption (SD of log recruitment = 0.5) was more optimistic than the R1 assumption, which probably reflects the model tendency to estimate large recent recruitment when unconstrained.
- The UA1 CPUE weighting assumption (Japan, Australia and New Zealand series all weighted equally) was more pessimistic in terms of current stock status than the UJA and UAJ assumptions. While there is considerable overlap among the model results corresponding to these sets of assumptions, we would have predicted that UJA (higher weighting on the Japanese CPUE series relative to Australia/New Zealand) would have had the more pessimistic outcome.
- The alternative growth/maturity/mortality assumptions had less of an impact on the current stock status estimates than expected, with a large degree of overlap among sets of model results for B(2007)/B(1997), and B(2007)/B(MSY).
- The alternative growth/maturity/mortality assumptions had important implications for the 5 and 10 year spawning stock projections. All of the fast growth curve models predicted substantial SSB increases by 2012 (assuming constant 2007 catches), while SSB remained stable near 2007 levels for the slow growth curve models.

The SWP stock status summary represents a synthesis of the results from all 192 models, from which we reach the following conclusions (estimates represent the median and range of the Maximum Posterior Density estimates; in the following section we illustrate that the model selection uncertainty is considerably broader than the statistical uncertainty estimated conditional on any individual model structure, so we consider the MPD estimates to provide a preferable reflection of the real uncertainty):

We consider relative biomass estimates for recent years to be the most reliable reference points, because they are the most closely linked to the highest quality data, and are reasonably robust to the alternative model assumptions explored. In 2006, Total Stock Biomass (TSB) was considered to be more reliable than Spawning Stock Biomass (SSB) reference points. However, given the recognition of additional uncertainty in growth rates in 2008, it is not clear that the TSB estimates are more robust than SSB. The MPD results from the plausible model ensemble indicate:

- median TSB(2007)/TSB(1997) = 0.69, range = (0.55 – 0.83).
- SSB(2007)/SSB(1997) = 0.58 (0.42 – 0.71).

The ratio of TSB relative to the biomass estimated to have occurred in the absence of fishing (TSBNF) provides a measure of the fishery impact on the population that might be more meaningful than the biomass ratio at two points in time if the population experiences non-stationary production dynamics (which these assessments tend to suggest to some degree).

- TSB(2007) / TSBNF(2007) = 0.58 (0.45 – 0.79)
- SSB(2007) / SSBNF(2007) = 0.43 (0.31 – 0.63).

The data are not sufficient to estimate a stock recruitment relationship reliably, and most or all models explored suggest some form of non-stationary (or at least highly variable) recruitment dynamics. This undermines the usefulness of the MSY-related reference points. However, in so far as these reference points have been calculated, the majority of MPD estimates from the plausible model ensemble suggest that biomass (total and spawning) are above levels that would sustain MSY and fishing mortality is probably below F(MSY).

- TSB(2007)/TSB(MSY) = 1.57 (1.22 – 2.06)
- SSB(2007)/SSB(MSY) = 1.98 (1.20 – 3.46)
- F(2007)/F(MSY) = 0.44 (0.18 – 0.67)

The stock projections (assuming deterministic future recruitment from the stock recruitment relationship, and constant catches relative to 2007 levels), suggest:

- TSB(2012) / TSB(2007) = 1.19 (1.03 – 1.54)
- SSB(2012) / SSB(2007) = 1.21 (0.91 – 2.07)
- TSB(2017) / TSB(2007) = 1.24 (1.05 – 1.64)
- SSB(2017) / SSB(2007) = 1.41 (0.94 – 2.30)
- TSB(2012) / TSB(MSY) = 1.89 (1.38 – 2.94)
- TSB(2017) / TSB(MSY) = 1.97 (1.43 – 2.99)

Overall the 2008 assessment suggests that current stock status and fishing mortality is in a less risky state than in 2006. This is not surprising given the recent drops in catch and effort. However, it is important to note that the recent increasing CPUE trends may be the combined result of reduced fishing effort and higher than average recent recruitment (see Figure 45 in the following section). There is no reason to expect that recruitment will be sustained at above average levels.

Table 5. Summary of model plausibility diagnostics and MPD stock status summaries (terms defined in text) for the Most Plausible Ensemble.

	Model Specification				
	Grid ES05 (192 models)			**Individual models at extreme range of MSY**	
Model fit Diagnostic	**median**	**min**	**max**	**pessimistic**	**optimistic**
ESS f=1	20	18	21	18	21
ESS f=2	54	50	58	55	54
ESS f=3	12	8	17	15	9
ESS f=4	238	203	287	236	246
ESS f=5	34	30	35	34	30
ESS f=6	5	5	5	5	5
ESS f=7	45	41	55	43	49
ESS f=8	23	15	37	23	15
ESS f=9	21	20	23	22	20
ESS f=10	15	15	16	15	16
ESS f=11	56	52	67	53	56
size bias f=all	16	13	19	16	17
cpueRMSE f=2	0.53	0.44	0.65	0.48	0.56
cpueRMSE f=4	0.18	0.13	0.32	0.16	0.18
cpueRMSE f=7	0.63	0.58	0.69	0.63	0.64
cpueRMSE f=11	0.29	0.22	0.38	0.30	0.29
Reference Point					
TSB2007 / TSB1997	0.69	0.55	0.83	0.64	0.77
SSB2007 / SSB1997	0.58	0.42	0.71	0.57	0.57
TSB2007 / TSBunfished	0.58	0.45	0.79	0.49	0.78
SSB2007 / SSBunfished	0.43	0.31	0.63	0.40	0.58
TSB2007 / TSBMSY	1.57	1.22	2.06	1.32	2.06
SSB2007 / SSBMSY	1.98	1.20	3.46	1.50	3.30
TSB2012 / TSB2007	1.19	1.03	1.54	1.14	1.30
SSB2012 / SSB2007	1.21	0.91	2.07	0.94	1.79
TSB2017 / TSB2007	1.24	1.05	1.64	1.21	1.32
SSB2017 / SSB2007	1.41	0.94	2.30	1.11	1.92
TSB2012 / TSBMSY	1.89	1.38	2.94	1.50	2.68
TSB2017 / TSBMSY	1.97	1.43	2.99	1.59	2.72
Aggregate F 2007	0.05	0.03	0.11	0.05	0.04
F2007 / FMSY	0.44	0.18	0.67	0.66	0.18
max(F / FMSY)	0.85	0.43	1.39	1.37	0.45
MSY (trunked mass *t*)	2381	1722	4119	1722	4119

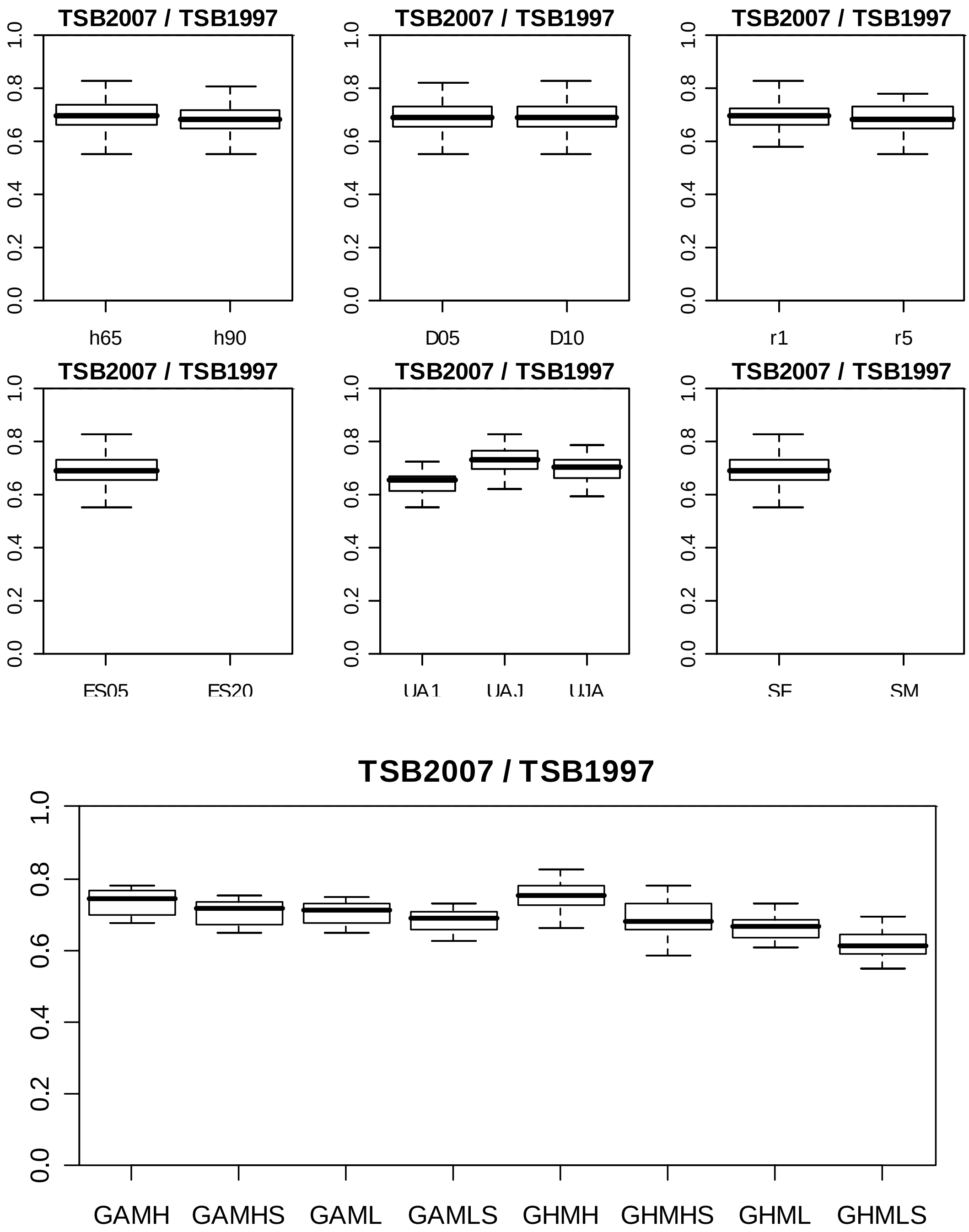


Figure 30. Summary of TSB(2007)/TSB(1997) MPD estimates from the South-West Pacific. Each panel summarizes 0, 25, 50, 75 and 100 percentiles from the distribution of 192 models in the Most Plausible Ensemble, partitioned according to individual model assumptions from the uncertainty grid (**Table 2**).

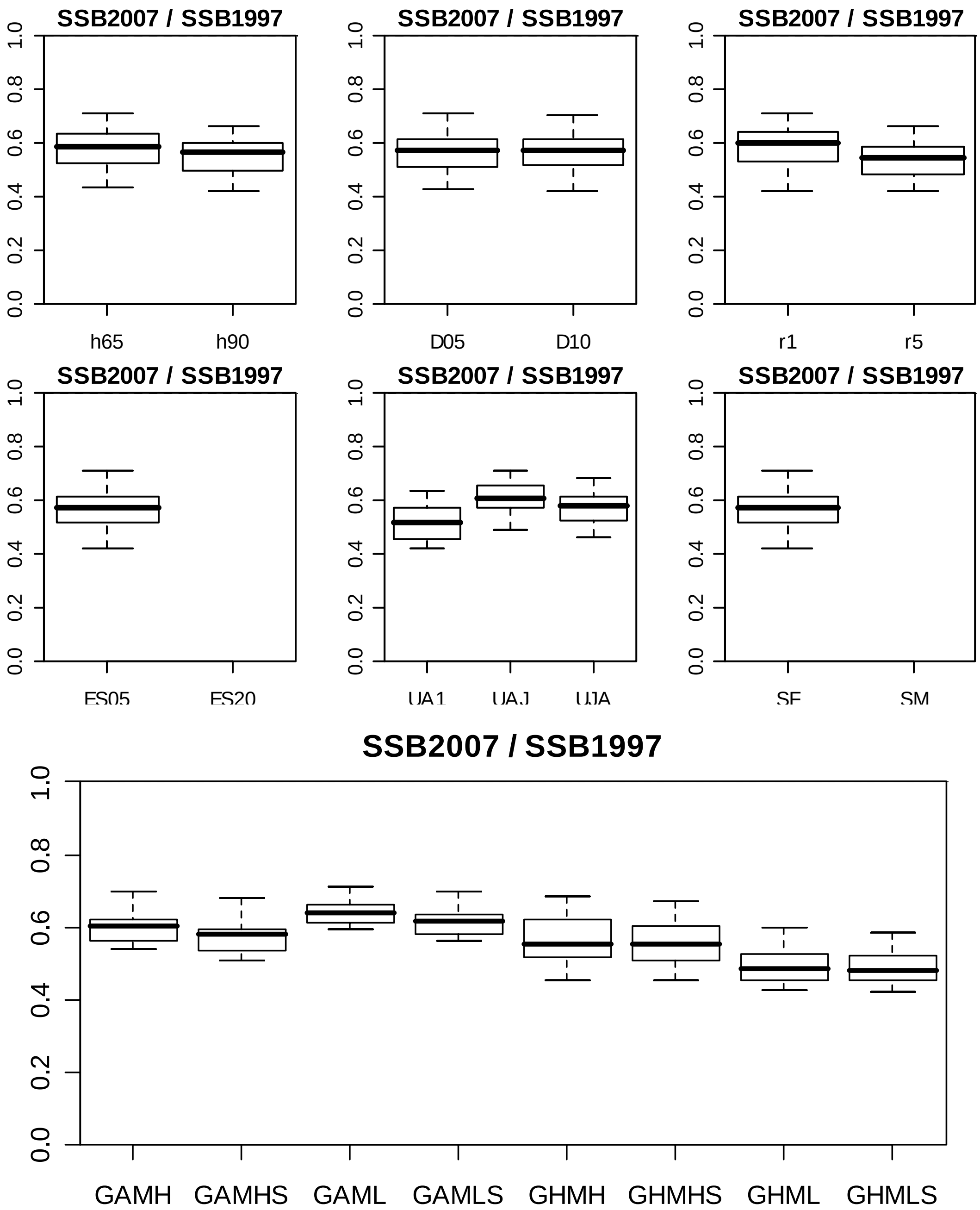


Figure 31. Summary of SSB(2007)/SSB(1997) MPD estimates from the South-West Pacific. Each panel summarizes 0, 25, 50, 75 and 100 percentiles from the distribution of 192 models in the Most Plausible Ensemble, partitioned according to individual model assumptions from the uncertainty grid (**Table 2**).

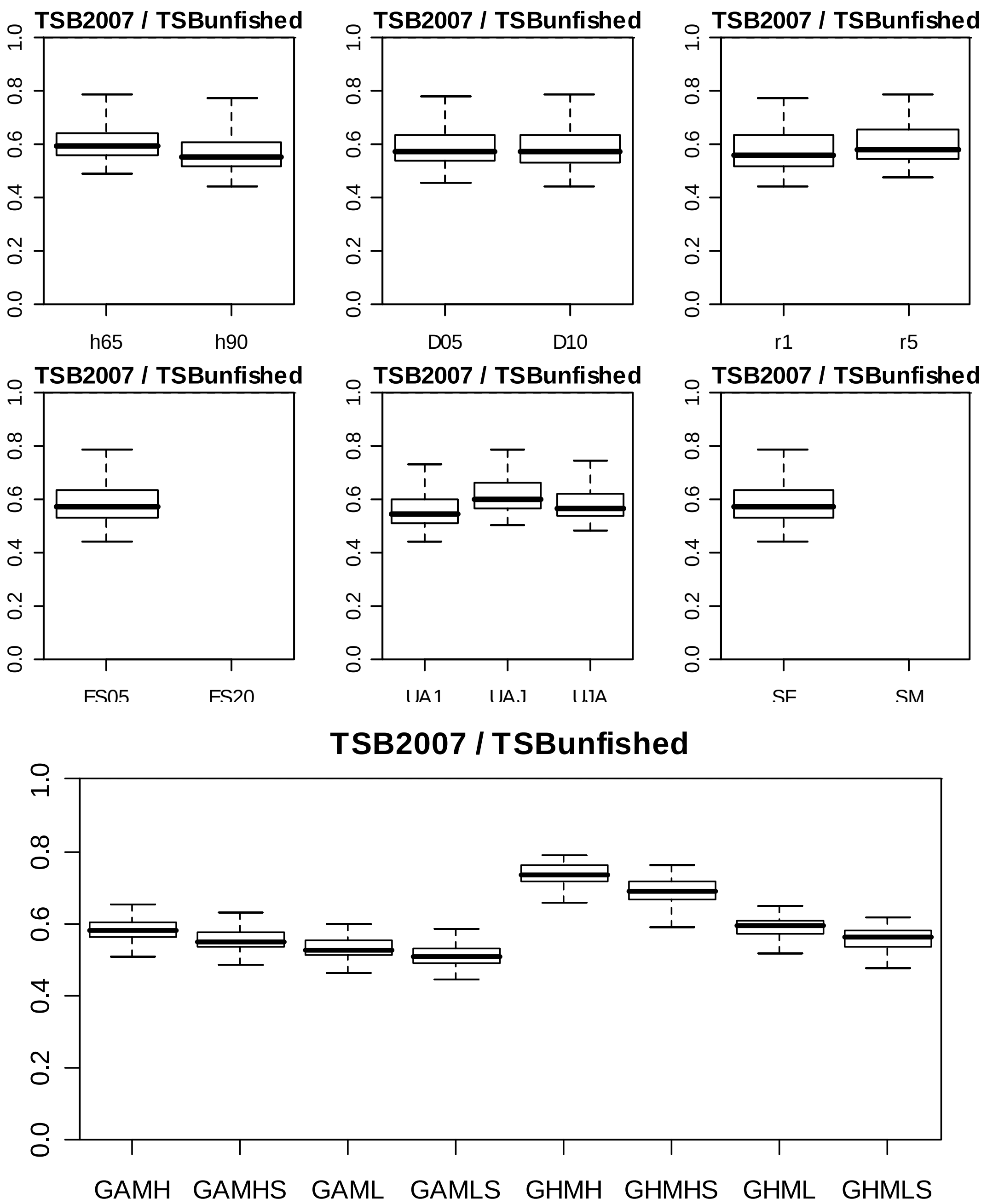


Figure 32. Summary of TSB(2007)/TSB(unfished) MPD estimates from the South-West Pacific. Each panel summarizes 0, 25, 50, 75 and 100 percentiles from the distribution of 192 models in the Most Plausible Ensemble, partitioned according to individual model assumptions from the uncertainty grid (**Table 2**).

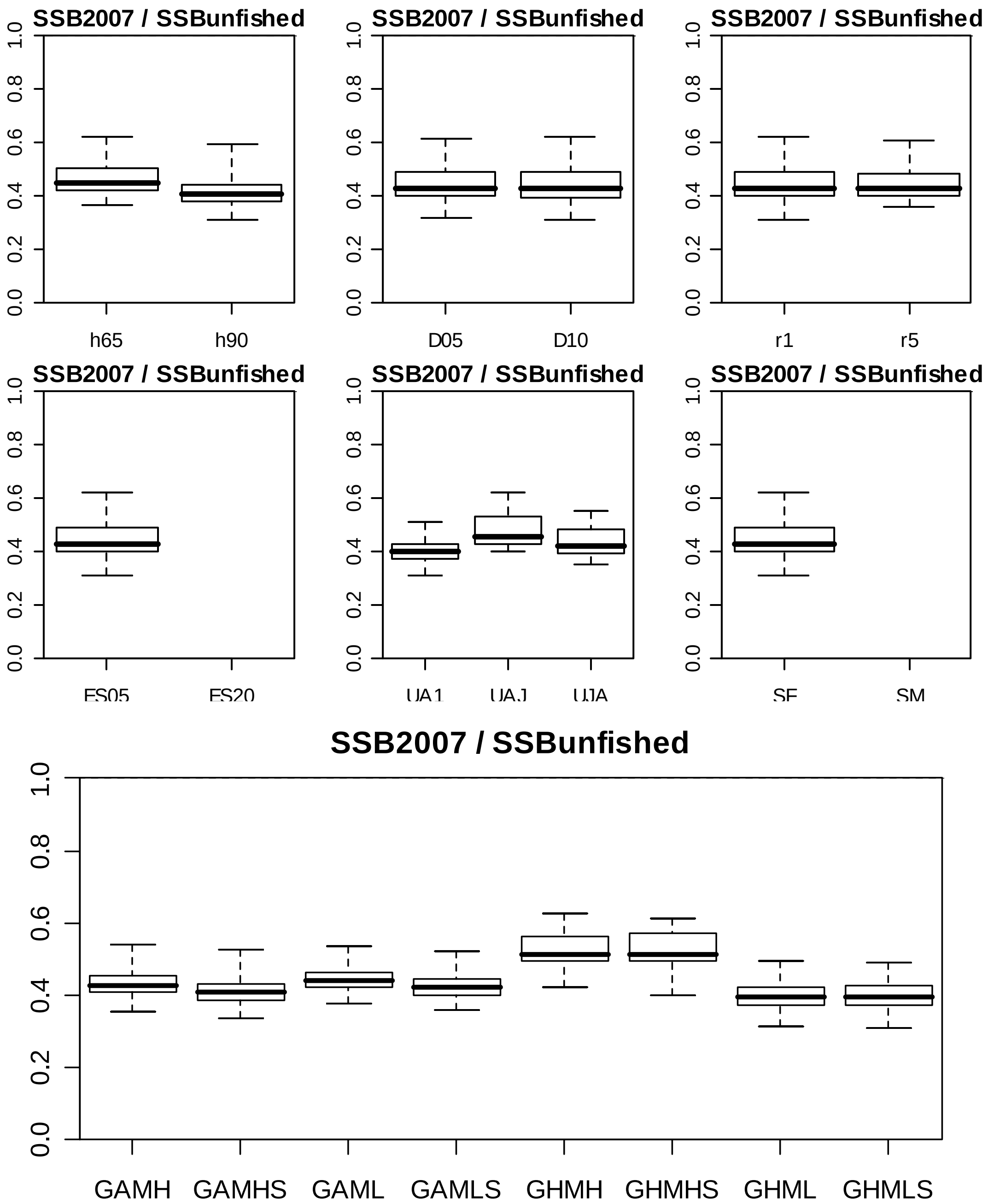


Figure 33. Summary of SSB(2007)/SSB(unfished) MPD estimates from the South-West Pacific. Each panel summarizes 0, 25, 50, 75 and 100 percentiles from the distribution of 192 models in the Most Plausible Ensemble, partitioned according to individual model assumptions from the uncertainty grid (**Table 2**).

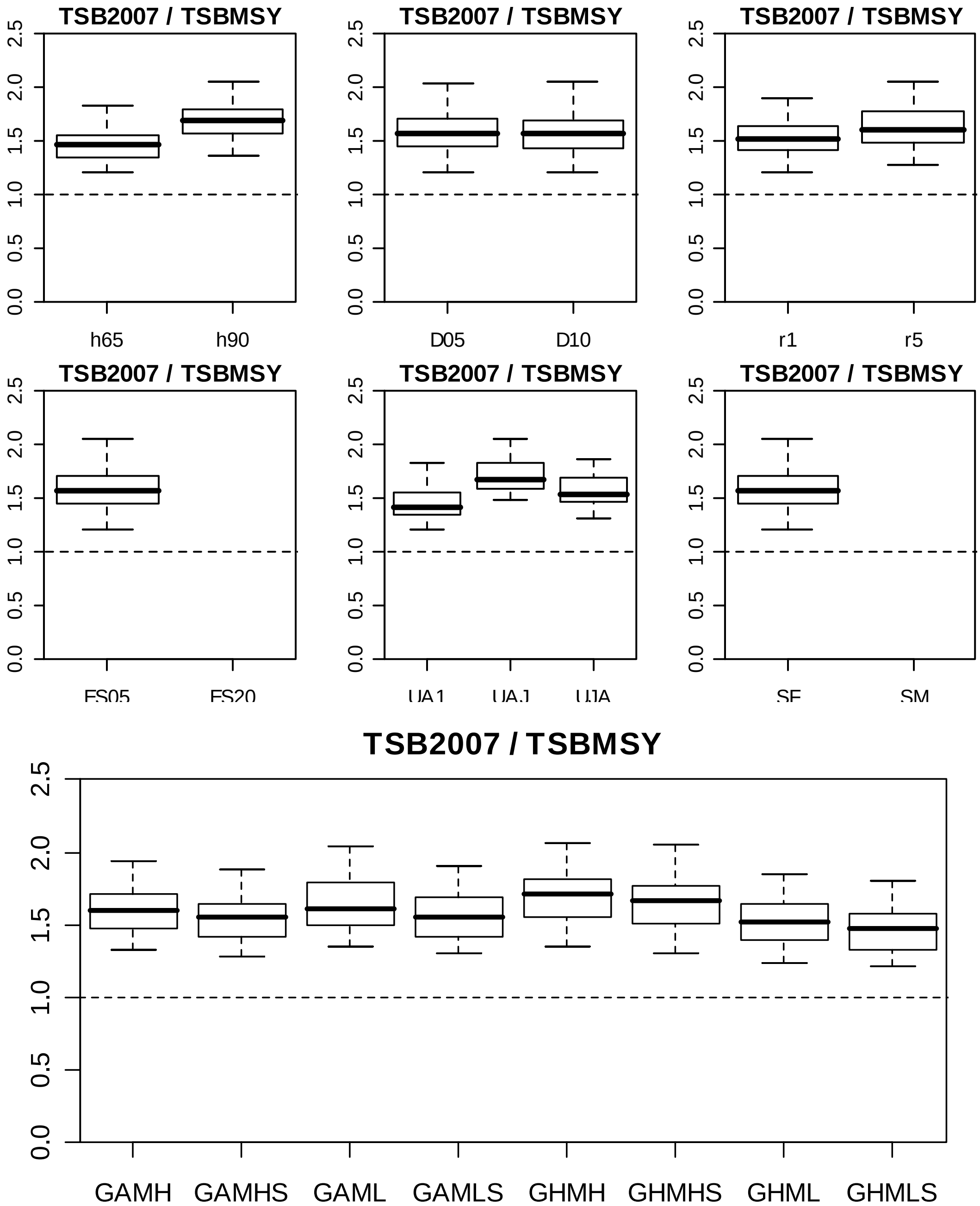


Figure 34. Summary of TSB(2007)/TSB(MSY) MPD estimates from the South-West Pacific. Each panel summarizes 0, 25, 50, 75 and 100 percentiles from the distribution of 192 models in the Most Plausible Ensemble, partitioned according to individual model assumptions from the uncertainty grid (**Table 2**).

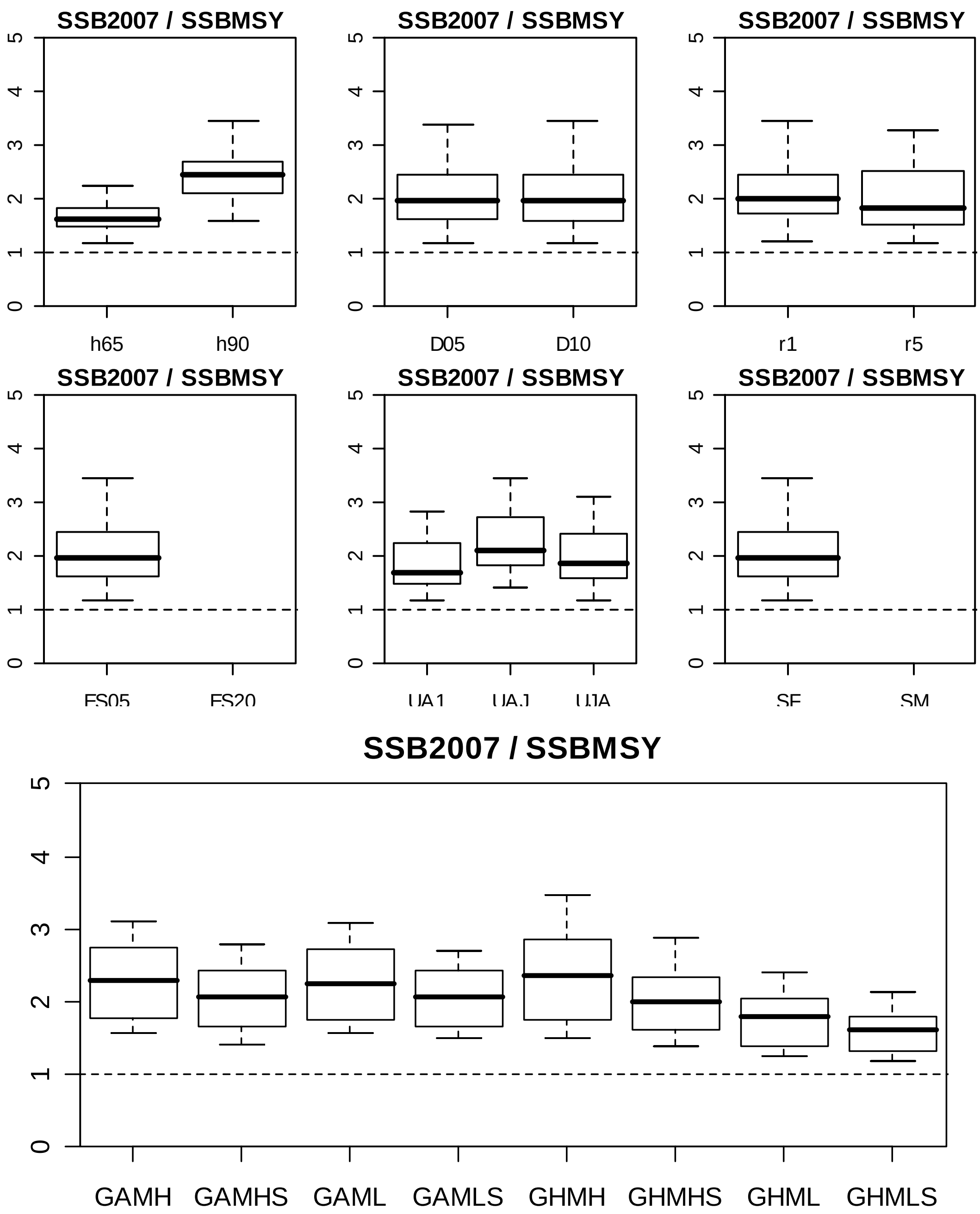


Figure 35. Summary of TSB(2007)/TSB(MSY) MPD estimates from the South-West Pacific. Each panel summarizes 0, 25, 50, 75 and 100 percentiles from the distribution of 192 models in the Most Plausible Ensemble, partitioned according to individual model assumptions from the uncertainty grid (**Table 2**).

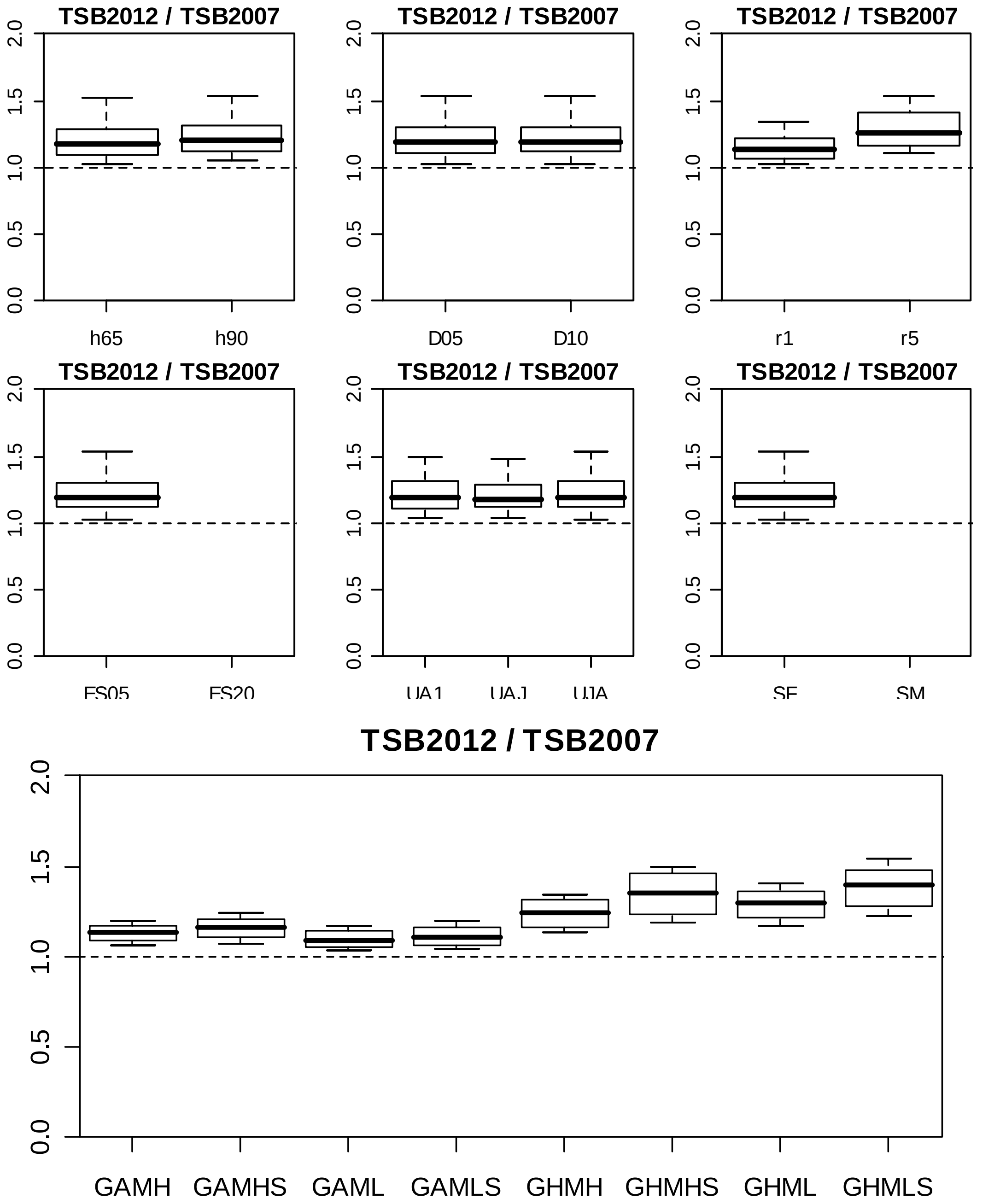


Figure 36. Summary of TSB(2012)/TSB(2007) MPD estimates from the South-West Pacific (assuming projected catch at 2007 levels and deterministic recruitment from the stock recruitment relationship). Each panel summarizes 0, 25, 50, 75 and 100 percentiles from the distribution of 192 models in the Most Plausible Ensemble, partitioned according to individual model assumptions from the uncertainty grid (**Table 2**).

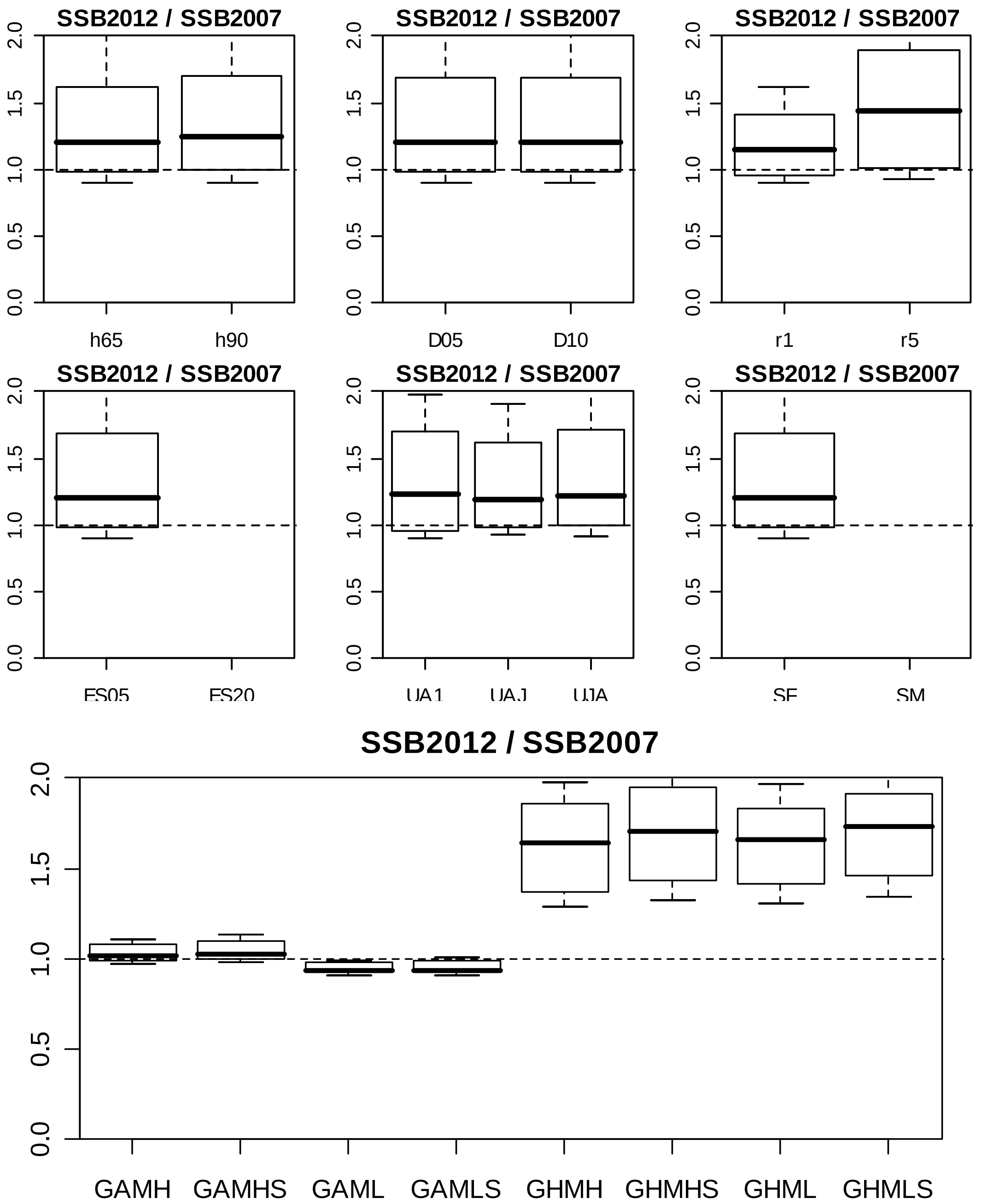


Figure 37. Summary of SSB(2012)/SSB(2007) MPD estimates from the South-West Pacific (assuming projected catch at 2007 levels and deterministic recruitment from the stock recruitment relationship). Each panel summarizes 0, 25, 50, 75 and 100 percentiles from the distribution of 192 models in the Most Plausible Ensemble, partitioned according to individual model assumptions from the uncertainty grid (**Table 2**).

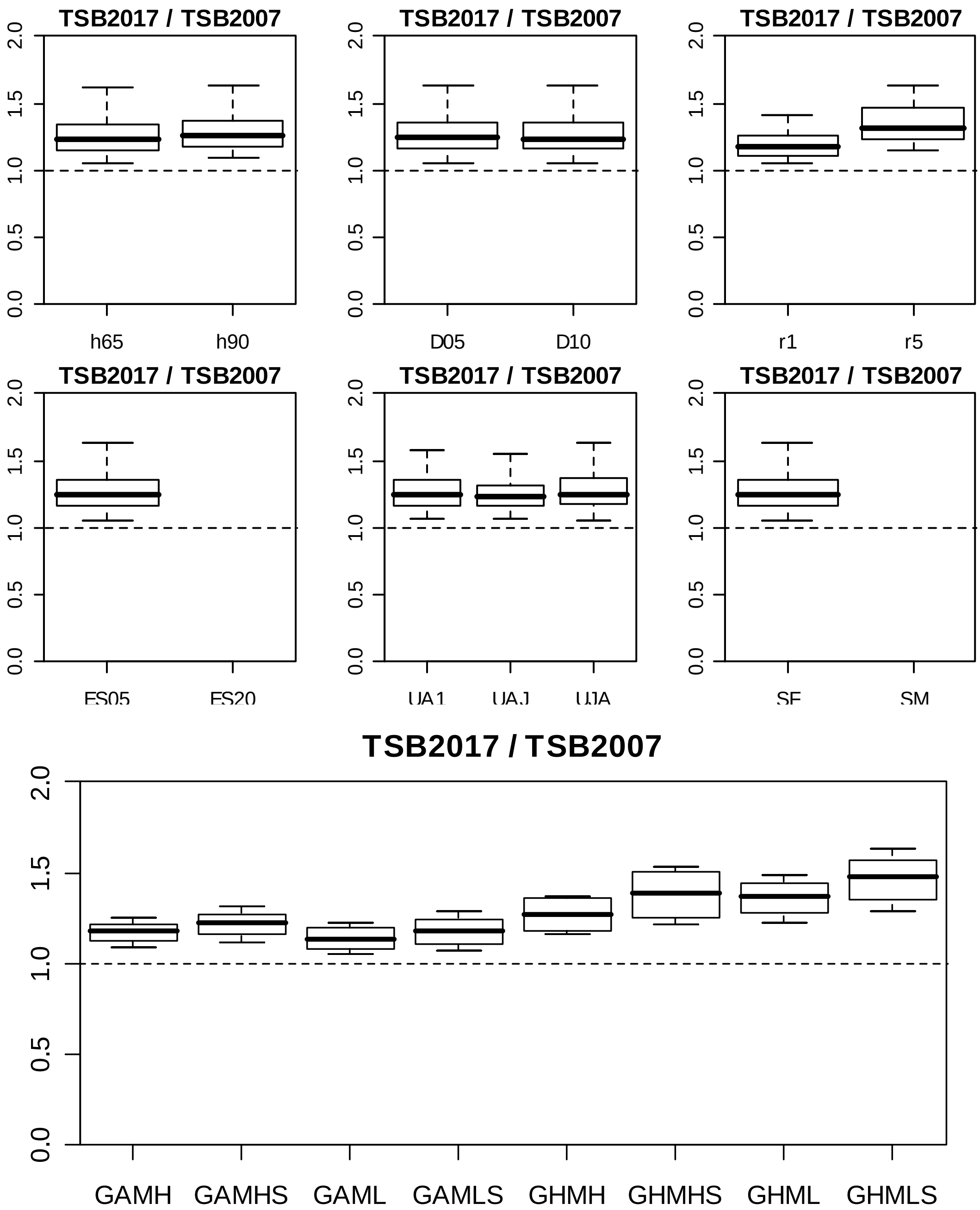


Figure 38. Summary of TSB(2017)/TSB(2007) MPD estimates from the South-West Pacific (assuming projected catch at 2007 levels and deterministic recruitment from the stock recruitment relationship). Each panel summarizes 0, 25, 50, 75 and 100 percentiles from the distribution of 192 models in the Most Plausible Ensemble, partitioned according to individual model assumptions from the uncertainty grid (**Table 2**).

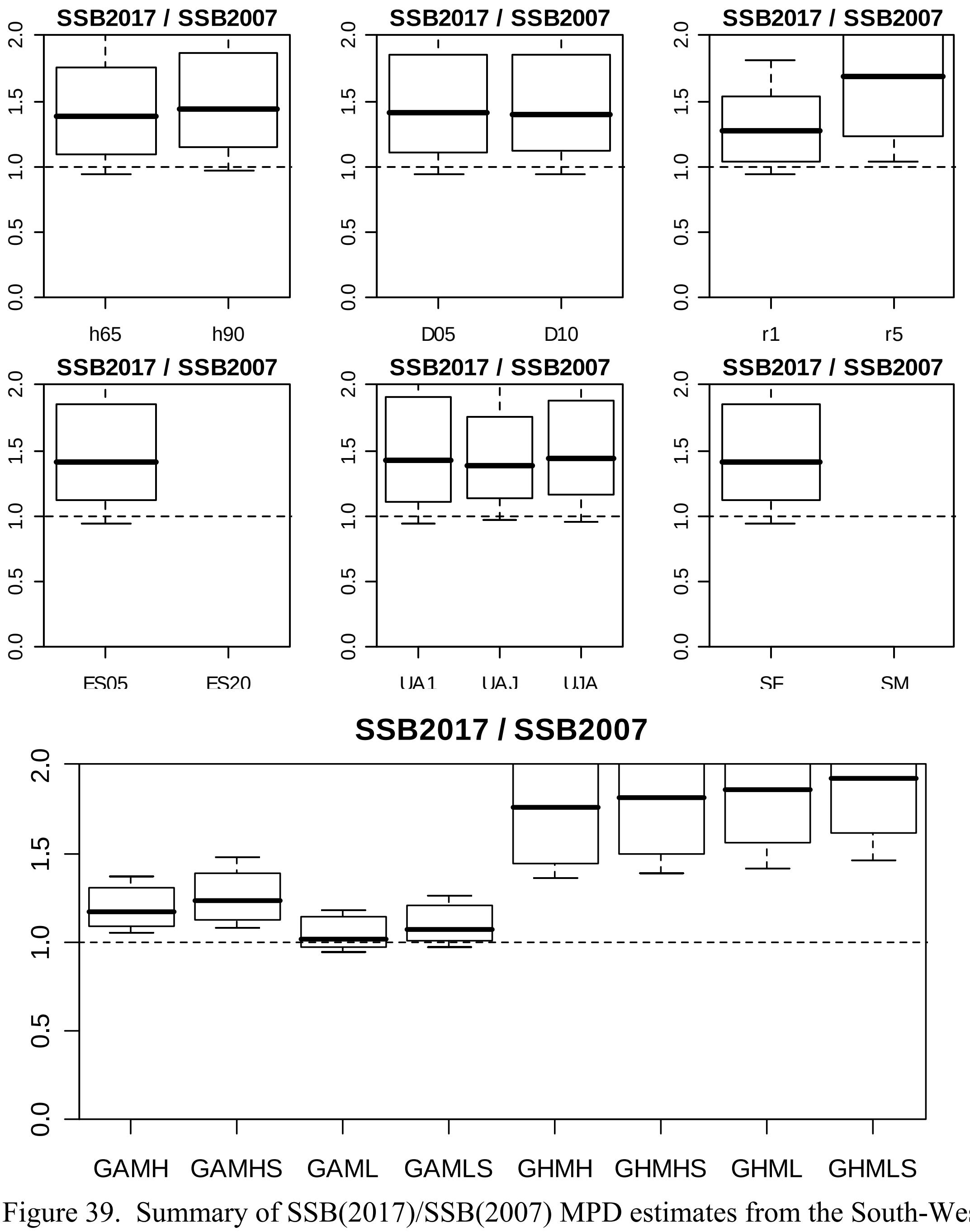


Figure 39. Summary of SSB(2017)/SSB(2007) MPD estimates from the South-West Pacific (assuming projected catch at 2007 levels and deterministic recruitment from the stock recruitment relationship). Each panel summarizes 0, 25, 50, 75 and 100 percentiles from the distribution of 192 models in the Most Plausible Ensemble, partitioned according to individual model assumptions from the uncertainty grid (**Table 2**).

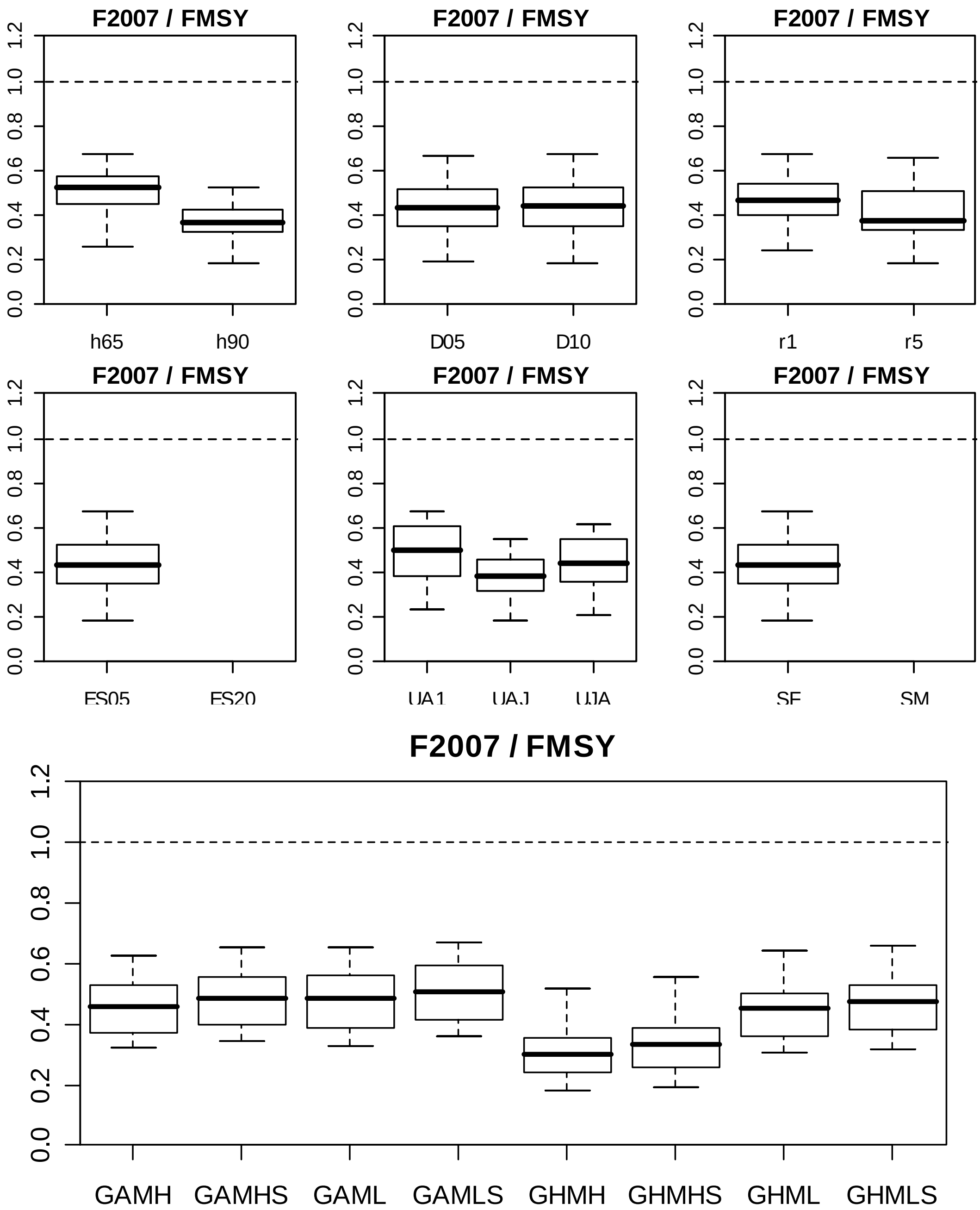


Figure 40. Summary of F(2007)/F(MSY) MPD estimates from the South-West Pacific. Each panel summarizes 0, 25, 50, 75 and 100 percentiles from the distribution of 192 models in the Most Plausible Ensemble, partitioned according to individual model assumptions from the uncertainty grid (**Table 2**).

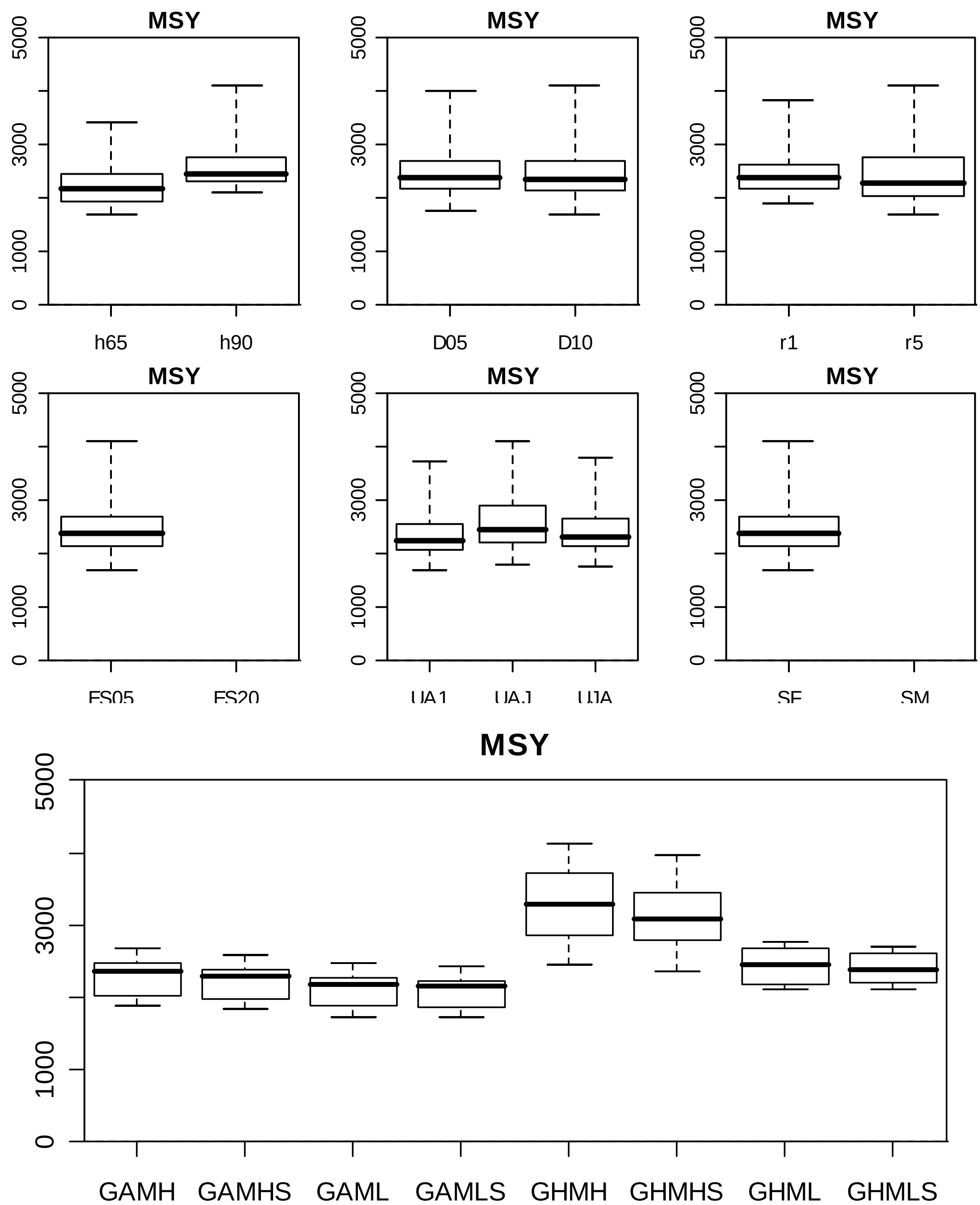


Figure 41. Summary of MSY (trunked mass in tonnes) MPD estimates from the South-West Pacific. Each panel summarizes 0, 25, 50, 75 and 100 percentiles from the distribution of 192 models in the Most Plausible Ensemble, partitioned according to individual model assumptions from the uncertainty grid (**Table 2**).

4.1.4 Comparison of model selection uncertainty and parameter estimation uncertainty

Mathematical theory provides rigorous methods for quantifying the uncertainty associated with statistical models, and provided that the model is correct, these uncertainty estimates should be very reliable. Unfortunately, in fisheries systems the models are never entirely correct, and methods for admitting uncertainty associated with alternative plausible models are not well developed. The following figures illustrate the uncertainty associated with the SWP model selection (or specification) uncertainty in relation to the confidence intervals generated by the statistical parameter estimation uncertainty. For clarity, only a subset of models from the Most Plausible Ensemble is discussed. This subset, hereafter referred to as the "Range-Set", corresponds to the 7 models with the most extreme MPD estimates for the following reference points:

- TSB(2007)/TSBNF(2007)
- TSB(2007)/TSB(MSY)
- F(2007)/F(MSY)
- MSY

Figure 42 illustrates the time series of Total Stock Biomass for the Range-Set of models. In this figure it is clear that the statistical confidence intervals do not provide a very good indication of the uncertainty that is observed among plausible model specifications. This general result is also clearly evident for F(t)/F(MSY) in Figure 43, absolute SSB(t) in Figure 44, absolute recruitment in Figure 45, and the sustainable yield curves in Figure 46. Figure 47 illustrates the relationship between TSB(2007)/TSB(MSY) and F(2007)/F(MSY).

We recognize that the narrow confidence limits for some of these models are related to our restrictive assumptions about variances (i.e. we do not believe that any of the CPUE series realistically should have an observation error CV of 0.1).

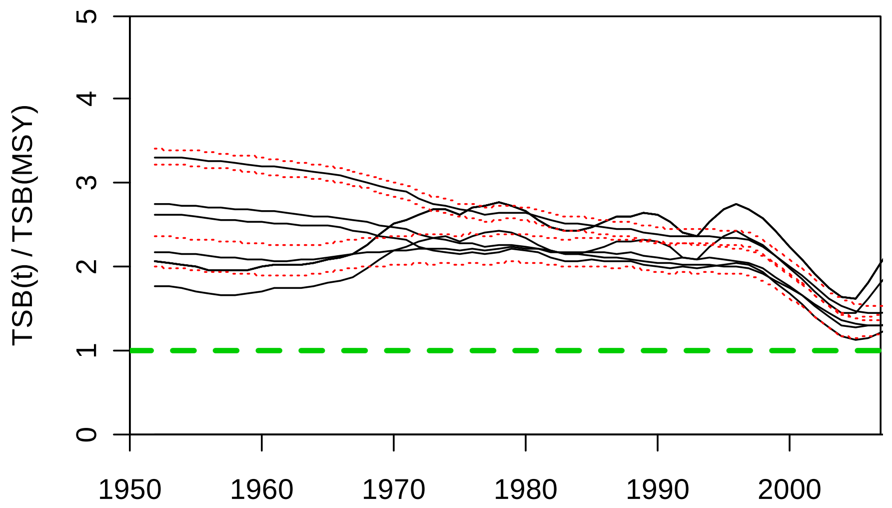


Figure 42. TSB(t) / TSB(MSY), for the "range-set" of models (the most extreme of the 192 ES05 model set on the basis of TSB(2007)/TSB(MSY), F(2007)/F(MSY), TSB(2007)/TSB(unfished) and MSY). Black lines indicate the MPD estimates for the individual models, while the dotted (red) lines indicate the upper and lower 95% confidence limits for two example models.

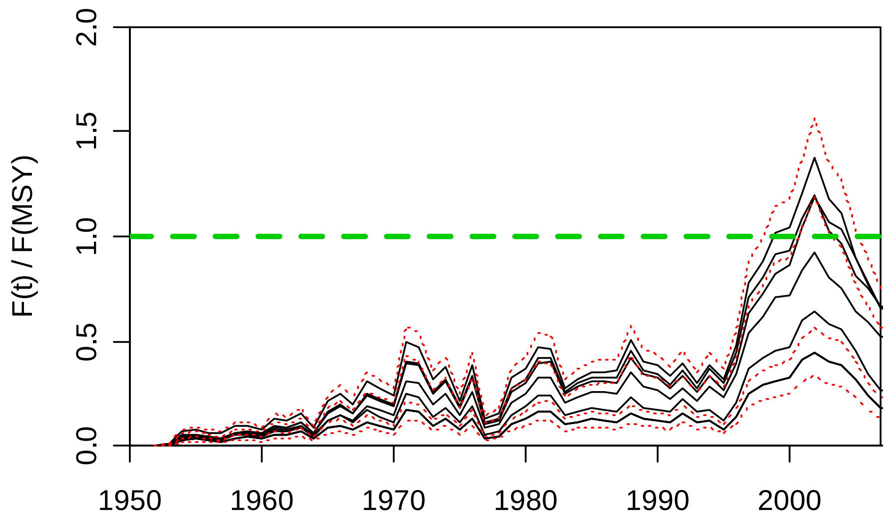


Figure 43. Fishing mortality relative to F(MSY) over time, for the "range-set" of models (the most extreme of the 192 ES05 model set on the basis of TSB(2007)/TSB(MSY), F(2007)/F(MSY), TSB(2007)/TSB(unfished) and MSY). Black lines indicate the MPD estimates for the individual models, while the dotted (red) lines indicate the upper and lower 95% confidence limits for two example models.

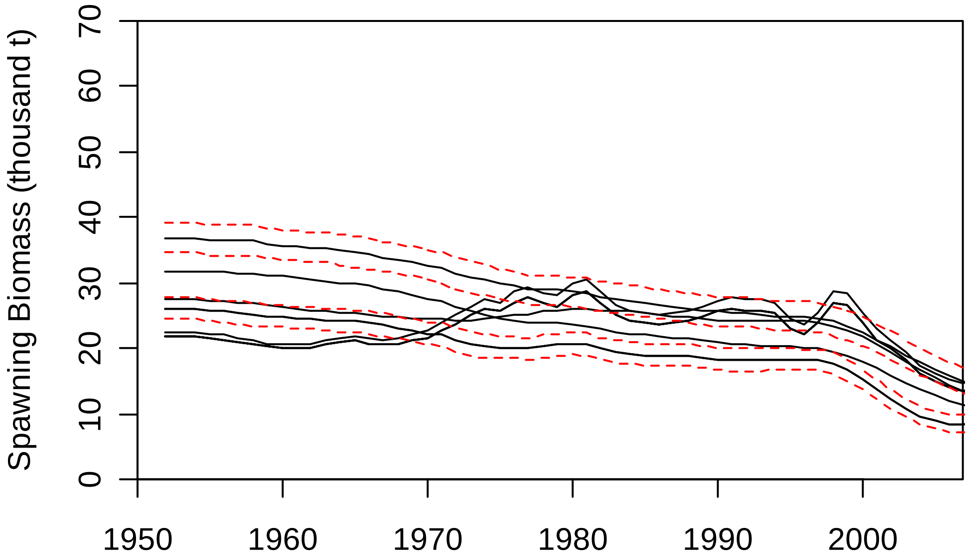


Figure 44. SSB(t) (thousand tonnes) for the "range-set" of models (the most extreme of the 192 ES05 model set on the basis of TSB(2007)/TSB(MSY), F(2007)/F(MSY), TSB(2007)/TSB(unfished) and MSY). Black lines indicate the MPD estimates for the individual models, while the dotted (red) lines indicate the upper and lower 95% confidence limits for two example models.

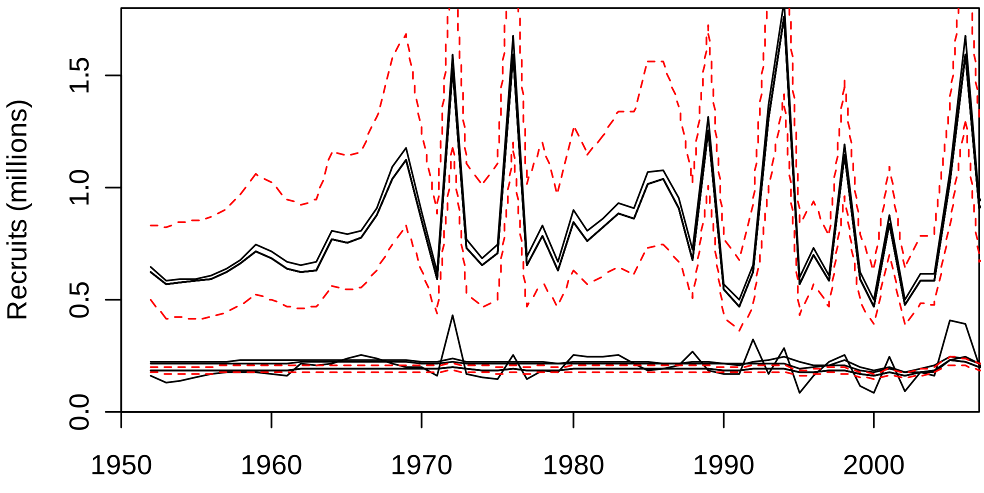


Figure 45. Recruitment time series for the "range-set" of models (the most extreme of the 192 ES05 model set on the basis of TSB(2007)/TSB(MSY), F(2007)/F(MSY), TSB(2007)/TSB(unfished) and MSY). Black lines indicate the MPD estimates for the individual models, while the dotted (red) lines indicate the upper and lower 95% confidence limits for two example models.

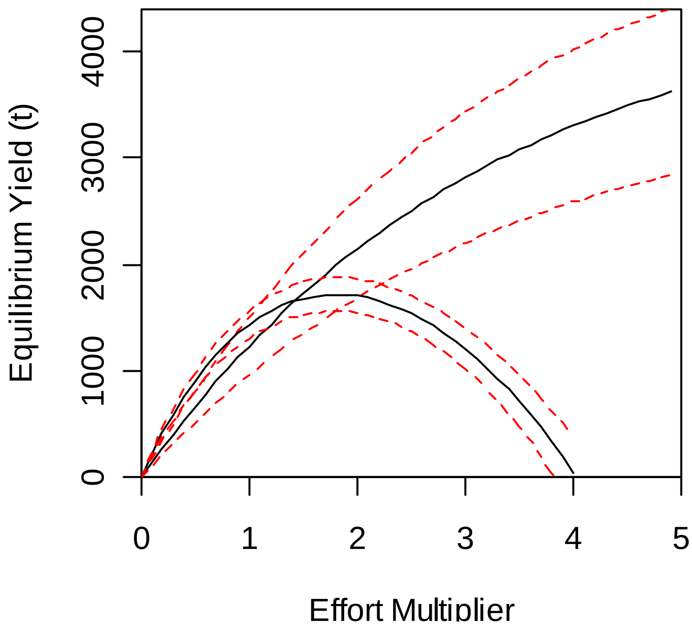


Figure 46. Sustainable yield curves for the most extreme of the models on the basis of MSY. Black lines indicate the MPD estimates for the individual models, while the dotted (red) lines indicate the upper and lower 95% confidence limits.

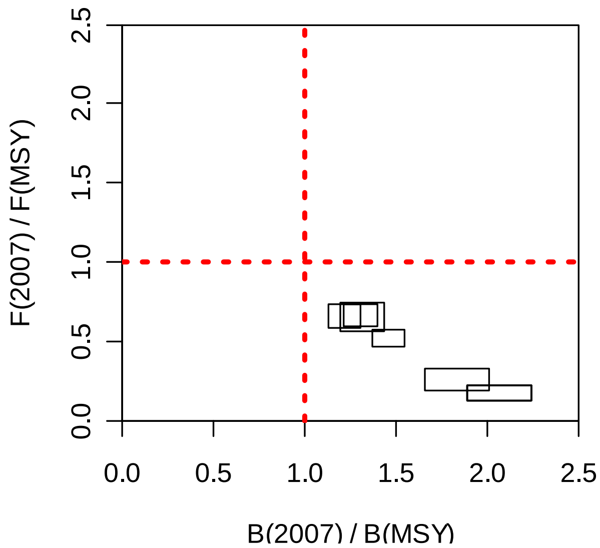


Figure 47. Summary plot comparing current fishing mortality, F(2007)/F(MSY), and total stock biomass, TSB(2007)/TSB(MSY), from the "range-set" of models extracted from the Most Plausible Ensemble. Boxes indicate the upper and lower 95% confidence limits (but not the covariance) for each individual model.

4.1.5 SWP Stock status summary relative to 2006 assessment

Figure 48 illustrates the summary relationship between estimated total biomass and fishing mortality in 2004 relative to MSY-related reference points extracted from the 2006 assessment. Superimposed on the 2006 figure are the (approximate) equivalent stock status estimates (again for 2004) derived from the Most Plausible Ensemble from the 2008 assessment. The 2008 estimates appear to be much more certain than 2006, and near the center of the distribution of estimates provided in 2006. This reduction in uncertainty is what might have been predicted given that the recent reduction in fishing effort seems to have been sufficient to break the "one-way-trip" nature of the fishery (e.g. Hilborn and Walters 1992) that was observed up to 2003-4, and hence might have provided informative contrast with which to improve the estimation of stock productivity. However, it is also likely that the revised spatial structure and constrained migration estimates have limited the number of ways that the models can fit the data (i.e. combining the northern and southern areas of the fishery removes one possible source of flexibility for the models to maintain large "cryptic biomass" reserves).

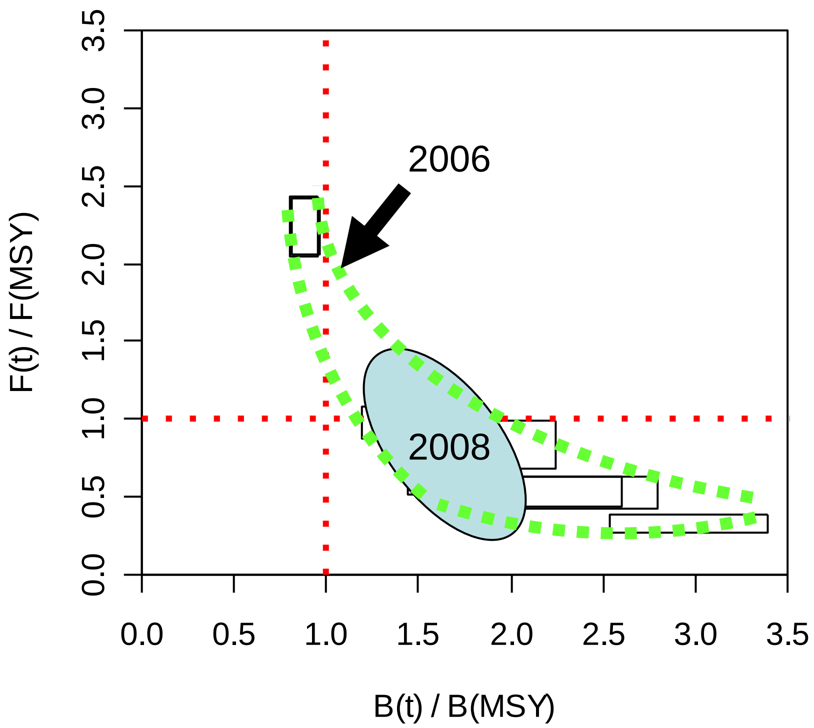


Figure 48. Summary plot comparing 2004 biomass and fishing mortality relative to MSY levels for the Most Plausbile Ensemble of models from the 2006 assesment (Kolody et al. 2006), and the range of models resulting from the 2008 assessment. Each black box indicates the 95% confidence intervals (though not the correlation) associated with an individual model from the 2006 assessment. The dashed (green) banana shape roughly outlines the space that was considered plausible in 2006. The blue oval roughly corresponds to the uncertainty space resulting from the 192 plausible models (with confidence limits) from the 2008 assessment.

4.1.6 Combined SWP-SCP Assessment

An assessment on the combined SWP-SCP was attempted, with an uncertainty grid of 144 models fit (**Table 3**). However, none of the results were satisfying, for reasons that were anticipated during the 2006 assessment and discussed at the swordfish assessment workshop (Anon. 2008). The nominal and standardized CPUE series that we were able to calculate from all the major fishing fleets in the SCP show a stable or continuous upward trend for the last several years (up to 20 or more depending on the series) despite the rapid increase in catches over the last decade (e.g. Figure 4, Figure 6, Figure 7). There is also a paucity of size composition data in the SCP (Figure 8). Thus there are no informative signals in either the CPUE or size composition data with which to estimate the impact of the fishery on the SCP stock.

An example of how the combined SWP-SCP models typically fit the observed CPUE series is illustrated in Figure 49. In general, the models produce an averaging effect in which the predicted CPUE is relatively flat, but with a general upswing over time. The observed declining trend in the SWP is not captured well by the models, and neither is the increasing trend in area 4 of the SCP (fishery 16). The SCP fisheries generally exhibit persistent biases in mean CPUE, with CPUE over-estimated in area 3, and under-estimated in area 4, particularly in the most recent 10-20 years. The bias arises (presumably) because the catchability of the Japanese fleet is shared across regions, and the model estimates some inconsistency in the estimated densities across regions. The bias effect is not as strong in the models that have greater flexibility in movement among regions. However, the divergence in the quality of fit trends among areas is always evident.

Most of the models estimate a trend in increasing recruitment for much of the duration of the fishery. In many cases, the models estimate very low stock recruitment curve steepness (i.e. a linear relationship between spawning biomass and abundance despite the restrictive priors, Figure 50). This is associated with the paradoxical implication that both biomass and recruitment are increasing over time, despite 3-4 decades of overfishing relative to F(MSY). In a few cases, the models suggest that, biomass is very large, and the fishery catch is negligible relative to the biomass (Figure 51). If the SCP is actually experiencing a gradual long-term change in recruitment productivity, then none of these models are very helpful for predicting what will happen in the future.

If we assume that all of the CPUE trends are reasonably accurate, then the models are not describing the conflicting signals among areas very well. To resolve the conflicting trends, presumably recruitment processes would need to be more localized, and migration among areas either needs to be very restricted, or subject to interannual variability of a form that MULTIFAN-CL cannot describe (i.e. random effects, as opposed to mean advection/diffusion).

However, another plausible explanation for the conflicting CPUE trends in the SCP might be found in the temporal trends in gear deployment and targeting practices. Without independent confirmation, one can rarely be confident that commercial effort standardization is effectively creating an unbiased relative abundance index, and this is particularly true in the SCP, where little operational data on setting procedures is available for the standardization analysis. It seems clear that the Taiwanese fleet has undergone a substantial operational shift toward targeting swordfish. Perhaps something similar, but more gradual, is occurring among the other DWF fleets.

We did not feel that it would be productive to pursue the combined SWP-SCP models further at this time. At present, there is no compelling evidence to indicate that the SCP swordfish fishery is over-exploiting the SCP population, but we do not consider the available data to be very convincing.

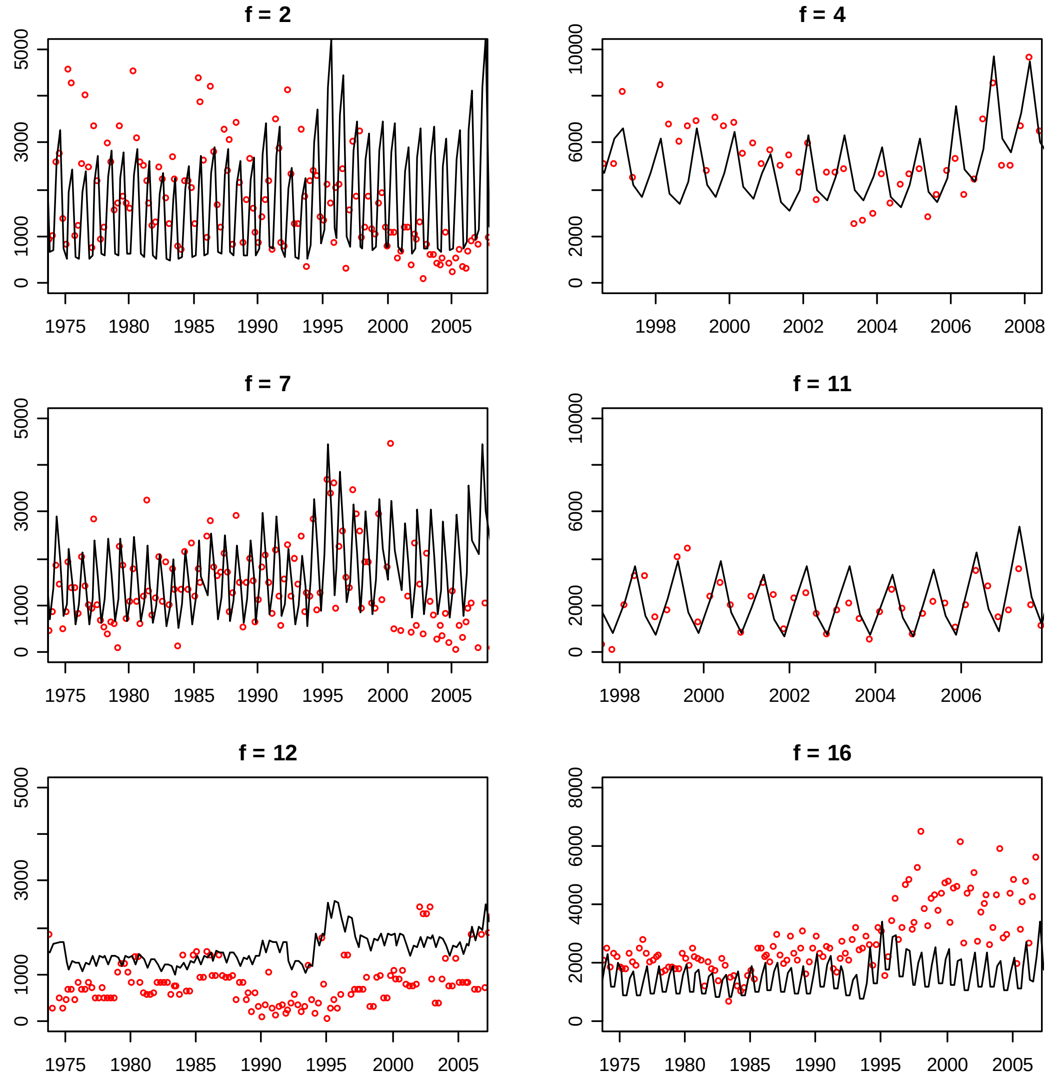


Figure 49. Typical illustration of the fits between predicted (solid lines) and observed (points) CPUE series for the combined SWP and SCP assessment. Fisheries 2 (Japan) and 4 (Australia) operate in SWP area 1, fisheries 7 (Japan) and 11 (New Zealand) operate in SWP area 2, fishery 12 (Japan) operates in SCP area 3, and fishery 16 operates in SCP area 4.

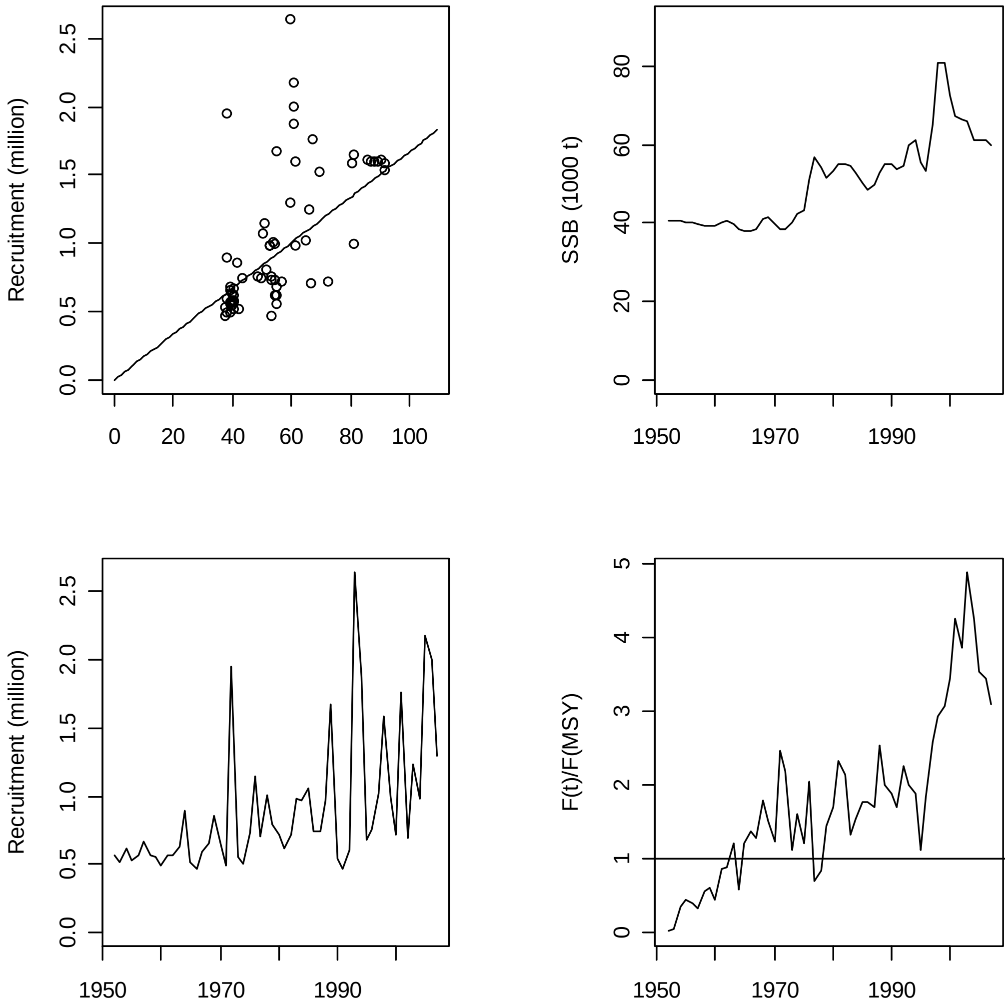


Figure 50. Representative dynamics estimated for the combined SWP and SCP assessment.

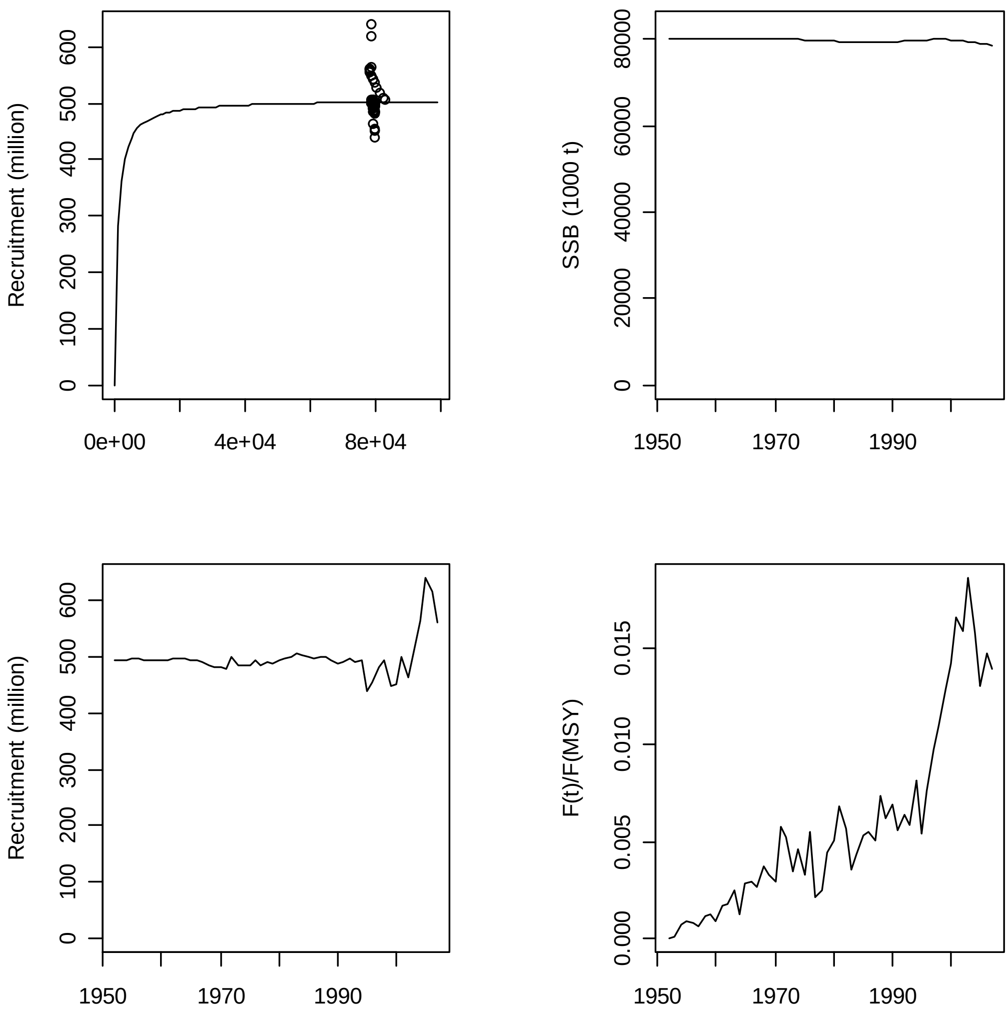


Figure 51. Representative dynamics estimated for the combined SWP and SCP assessment.

4.2 Future Assessment Considerations

Major assessment uncertainties and potential means for resolving the uncertainties are discussed below.

The appropriate spatial structure for use in the south Pacific swordfish assessment remains unclear. There seem to be reasonable arguments for assuming that the SW Pacific forms at least a semi-independent population. The SCP might form another semi-independent population, or it might be more closely linked with populations from the Eastern or Northern Pacific. On the basis of maturity studies, Mejuto et al. (2008) suggest that there is a major spawning ground in the central equatorial Pacific, which would presumably contribute to the SCP population as defined here. Kolody et al. 2006 and Davies et al. 2006 explored alternative spatial assumptions related to homogenous mixing vs site-fidelity with seasonal migration. However, the 2006 modelling studies, combined with genetic, demographic and tagging studies since 2006 have prompted these migration ideas to be revisited in the context of a broader spatial scale (Figure 52). Improved assessment of the SCP might need to involve a further expansion of the assessment domain.

Genetic connectivity studies might help to inform this debate further, if appropriate genetic markers can be identified, and reasonable sample coverage can be obtained. However, given that relatively small numbers of long distance migrations can blur genetic boundaries, we might not gain much understanding of the mixing with adjacent Pacific (and Indian) Ocean populations unless substantial numbers of tags can be deployed. This could include conventional, electronic and/or genetic tags. While PSAT tags can provide high resolution detail of seasonal movements, the value of conventional tags for revealing long term mixing patterns should not be under-estimated.

Irrespective of the population connectivity studies, it seems unlikely that the SC Pacific assessment will be substantively improved without better data from the region. Any additional information that can be gathered to help quantify the impact of the fishery in the SCP would be worthwhile. We note that operational level data exist for a number of fleets, and we would encourage collaborative research with other nations in the analysis of these data. In particular it was noted that operational level data from the Taiwanese fleet exists (and perhaps may be obtainable from the USA records from Pago Pago). The Spanish longline fleet represents a new and attractive data opportunity, given their comprehensive biological sampling programs, and a time series that is starting to be long enough to discern trends.

All fleets should conduct adequate biological sampling. There is very little historical size sampling for most fleets (particularly in the SCP), and the best data that are available suggest that the catch size composition has declined dramatically since the late 1990s (in the SWP). Stratified random sampling by sex, area, and time is encouraged for all fleets. From an assessment point of view, collection of hard parts for direct age estimation would actually be more informative than size, as size is primarily used as an indirect approximation for age.
Studies that improve our understanding of the relationship between catch rates and abundance are encouraged. This includes collection of additional data about fishing practices from all fleets (e.g. fishing master decisions about where and when to fish, species targeting and gear configuration), and ecological studies of fish distributions (e.g. using electronic tags and oceanographic data to understand swordfish habitat preferences). Application of standard survey techniques using commercial gear might be a powerful tool for quantifying relative abundance. Comparisons between standardized gear and current fishing practices would be

valuable for understanding the implications of changing fishing methods on commercial catchability and selectivity.

Young et al. (2008) have illustrated that there remains substantial uncertainty about the methods of estimating ages for swordfish. Different labs use different methods, and we are not aware of any convincing age validation studies for swordfish. We would strongly encourage attempts to directly validate fin ray annulus counts. It would be cost effective to add oxy-tetracycline injection along with tagging studies. It is also worth reducing the uncertainty in maturity estimates, but most of this uncertainty seems to be dependent on the age estimation problem.

These types of stock assessment models are critically dependent on the quantification of total fishery removals, and these data are generally assumed to be known with very little error. For swordfish, we are not aware of any evidence to suggest that there are major errors in the catch data, but observations of recent discarding and historical information from the various fleets (and markets) might help to validate this assumption.

There is strong evidence for sex-specific growth and migration characteristics in swordfish. Wang *et al*. (2005) use swordfish assessment simulations to illustrate that model biases can be reduced through the inclusion of sex-dimorphism. This may be important at some point, however, in the short-term, it seems likely that other sources of assessment uncertainty are more important for this species (e.g. age validation is likely required before sex disaggregation can be meaningful).

Very little is known about natural mortality of swordfish. Given the divergent growth and migration characteristics between the sexes, it would not be surprising if mortality also differed. Concerted tagging studies, and direct age estimation from routine hard parts sampling (by sex) would be expected to help to reduce these uncertainties.

The unfortunate fact that stock assessments cannot produce accurate estimates about many of the key quantities of interest to managers has been recognized in many fisheries (often with much better data than this one), and has been a part of the growing popularity of formal methods for Management Strategy Evaluation (MSE, or equivalently, Management Procedures or Harvest Strategies). In 2005, the Australian Department of Agriculture, Fisheries and Forestry initiated a program to have domestic harvest strategies in place for target species of all commonwealth managed fisheries (e.g. Campbell et al. 2007). MSE is perceived to have a number of advantages over other methods of fisheries management, and foremost among these advantages is the use of pre-agreed feedback decision rules that are simulation tested to provide long term management performance that is robust to the stock assessment uncertainty. We consider it to be a positive move for the effective management of the Australian ETBF fishery, and encourage a similar, multilateral approach for the straddling and migratory stocks of the WCPO, including swordfish.

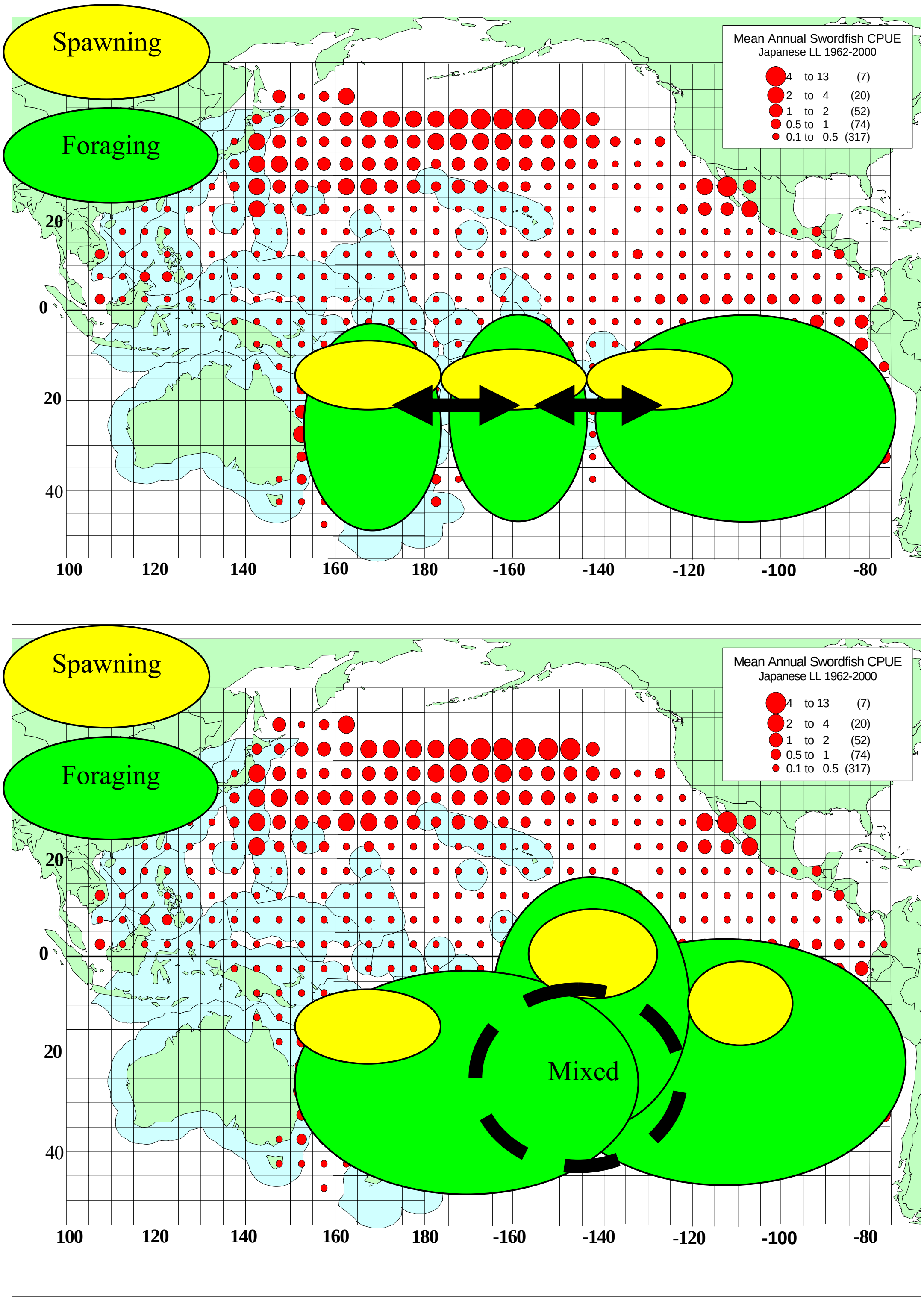


Figure 52. (Figure 10 from Kolody and Davies 2008) Schematic representation of two possible stock structure represenions for South Pacific swordfish: top panel = homogenous mixing, bottom panel = foraging site fidelity.

5 Conclusions

- This paper describes an attempt to assess the status of the South-West and South-Central Pacific swordfish population(s) using MULTIFAN-CL software to integrate the available fisheries data (total catch in numbers, standardized catch rates, and catch size composition) with biological studies (on age, growth, maturity, stock structure and migration dynamics). The main differences from the 2006 assessment included:
    - an explicit attempt to include the South-Central Pacific region in addition to the South-West Pacific
    - 2-3 additional years of data were added, including a period of recent catch and effort declines in the SWP that potentially provides informative contrast to the time series
    - A revision of the spatial structure and movement rate assumptions in relation to recent tagging studies in the SWP.
    - Recognition that swordfish growth rate and maturity estimates are more uncertain than previously recognized due to a lack of independent validation studies.

- Assessment results for the SWP are based on a synthesis of 192 model specifications that appear to be plausibly consistent with the data and our prior expectations of the fishery dynamics. The results are more consistent among models than observed in 2006. This is thought to represent the combined effect of i) recent informative contrast in the catch/effort series breaks the "one-way trip" history of the fishery, and ii) the revised spatial structure and movement assumptions constrain the model capacity for estimating "cryptic biomass". SWP Stock status reference points based on Maximum Posterior Density estimates include:
    - TSB(2007)/TSB(1997) median = 0.69, range = (0.55 – 0.83)
    - TSB2007 / TSB1997 = 0.69 (0.55-0.83)
    - SSB2007 / SSB1997 = 0.58 (0.42-0.71)
    - TSB2007 / TSBunfished = 0.58 (0.45-0.79)
    - SSB2007 / SSBunfished = 0.43 (0.31- 0.63)
    - TSB2007 / TSBMSY = 1.57 (1.22 - 2.06)
    - SSB2007 / SSBMSY = 1.98 (1.20 - 3.46)
    - TSB2012 / TSB2007 = 1.19 (1.03 - 1.54)
    - SSB2012 / SSB2007 = 1.21 (0.91 – 2.07)
    - TSB2017 / TSB2007 = 1.24 (1.05 -1.64)
    - SSB2017 / SSB2007 = 1.41 (0.94 - 2.30)
    - SSB2012 / TSBMSY = 1.89 (1.38 - 2.94)
    - TSB2017 / TSBMSY = 1.97 (1.43 - 2.99)
    - Aggregate F 2007 = 0.05 (0.03 - 0.11)
    - F2007 / FMSY = 0.44 (0.18 - 0.67)
    - max(F / FMSY) = 0.85 (0.43 -1.39)
    - MSY (trunked mass tonnes) = 2381 (1722 – 4119)

  Confidence intervals based on the statistical estimation uncertainty have been calculated and illustrated for some of these reference points, however, the model selection uncertainty represented in the MPD estimates is broader, and considered to be a more realistic reflection of uncertainty.

- An attempt was made to model the combined SWP-SCP. However, none of the results were satisfying, due to problems with the SCP data that were anticipated during the 2006 assessment and discussed at the swordfish assessment workshop in April 2008 (Anon. 2008). The nominal and standardized CPUE series from all the major fishing fleets in the SCP are either stable or increasing over the last 20 years, despite a rapid increase in catches. There is also a paucity of size composition data in the SCP. Thus there are no informative signals in either the CPUE or size composition data with which to quantify the fishery impact on the SCP stock. If it is assumed that the SCP CPUE indices provide a true reflection of abundance trends then:
    - The SCP probably is experiencing a gradual long-term change in recruitment productivity and historical data provide little indication of what is going to happen in the future, and
    - The SCP swordfish population is not rapidly mixing with the SWP population, as the general CPUE trends in the two areas are in opposite directions despite a similar magnitude of catch removals.

  If so, it follows that the SWP population should be assessed independently of the SCP population (and the SCP population might be more appropriately assessed with the North-Central or Eastern Pacific populations).

  However, it remains possible that the increasing CPUE trends are the result of changes in gear deployment (targeting) practices in the SCP. Overall we did not find any compelling evidence to suggest that the swordfish fishery is over-exploiting the SCP population, but we do not consider the available data to be very convincing. Collection and exchange of operational level logbook data and improved catch composition sampling is encouraged. We recognize that the extensive observer programs in the Spanish fleet might prove very informative in future assessments and encourage more collaboration in future assessments.

- Major assessment uncertainties include:
    - Stock-recruitment relationship cannot be reliably estimated, and there is some evidence for shifting recruitment regimes in both the SWP and SCP.
    - Commercial catch rates are used as relative abundance indices, and we do not know how effective the standardization methods are. Recent conflicting trends between the Australia/New Zealand vs: Japanese series is a concern. Data for standardization analyses in the SCP are poor
    - The migratory link between the SWP, SCP and broader Pacific (and possibly Indian Ocean) populations remains poorly quantified.
    - Growth rates, maturity schedules and natural mortality for this species remains poorly quantified.

- Recommendations to improve future assessments are provided, including:
    - Comparison of methods for estimating age and maturity of swordfish are encouraged.
    - Direct validation of ageing methods should be undertaken (e.g. oxy-tetracycline marking in conjunction with tagging).
    - Collection of additional gear deployment (targeting) data to improve understanding of commercial catch rate interpretation (logbook data for the Taiwanese fleet are known to exist). Ideally, this might include some portion of the commercial fleet setting standardized gear with consistent survey methodology.
    - Research into the relationship between fish distributions and movement in relation to oceanographic variability should assist in interpreting catch rates.

- Collection and exchange of better catch composition data for all fleets, ideally including length, mass, and sex, plus hard parts for direct age estimation. Existing data (e.g. Spanish size composition data for 2005-7 should be included next time)
- Electronic, conventional and genetic tagging programs are encouraged to help quantify migration characteristics within the SW-SC Pacific and between adjacent waters.

- We expect that improvements to the assessment will continue to be made. However, we suggest that the most productive use of the assessment advice in the short term might be to use Management Strategy Evaluation to develop harvest strategies that are robust to the major uncertainties identified.

6 Acknowledgements

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8 Appendix 1 – Batch file indicating South-West Pacific swordfish assessment Multifan-CL switches and phased parameter estimation

The assessment was run using the windows version of mfclopt.exe executable compiled May 2006. In the following, "#switch" indicates options that were tested as part of the model uncertainty grid. Other elements in the model uncertainty grid (e.g. growth, maturity and natural mortality) were controlled through the .ini input files.

```
#doitall grid entry
# generic shell for batch processing of MFCL model fitting across a balanced grid of factors
# 1) remove existing files that might confuse process if errors encountered
# 2) conventional doitall with switches flagging parts to replace
# 3) rename results to grid identification
rm *.par
rm 01.*
rm plot.rep
rm length.fit
rm weight.fit
rm *.hes
rm *.var
#! over bin over sh
#
#rm *.par
#------------------------
#  PHASE 0 - create initial par file
#  ------------------------
#
#if [ ! -f 00.par ]; then
#  mfclo32May2808 switch_frqA SWO5P001.ini 00.par -makepar
#fi
#  ------------------------
#  PHASE 1 - initial par
#  ------------------------
#
if [ ! -f 01.par ]; then
  #mfclo32May2808 switch_frqA 00.par 01.par -file - <<PHASE1
  #mfclo32May2808  swo2007A12F11003.frq 002007A12F11001.inpar 01.par -file - <<PHASE1
#switch .inpar options (includes Growth, M, Mat, Migration rate, SR steepness)
#inpar switch ###: mfclo32May2808  swo2007A12F11003.frq  ###: 01.par -file - <<PHASE1
  2 113 1        # estimate initpop over totpop scaling parameter
  1 32 3         # sets "a slightly faster initial control sequence" standard initial estimation scheme
  1 141 3        # sets likelihood function for LF data to normal
  2 57 1         # sets no. of recruitments per year to 1
#  2 69 1        # sets generic movement option (now default)
  2 94 1 2 95 10  # initial age structure based on estimated M (assume virgin)
  -999 26 2      # sets length-dependent selectivity option
  -999 57 3   # use cubic spline for selectivity
  -999 61 5   # number of parameters in cubic spline
# grouping of fisheries with common selectivity
   -1 24 1
   -2 24 1
   -3 24 2
   -4 24 1
   -5 24 1
   -6 24 1
   -7 24 1
   -8 24 3
   -9 24 1
  -10 24 1
  -11 24 4
#  -1 29  1     #group catchabilities to prevent weirdness (deviations ?)
#  -2 29  2     #group catchabilities
```

```
# -3 29 3      #group catchabilities
# -4 29 4      #group catchabilities
# -5 29 5      #group catchabilities
# -6 29 6      #group catchabilities
# -7 29 7      #group catchabilities
# -8 29 8      #group catchabilities
# -9 29 9      #group catchabilities
# -10 29 10      #group catchabilities
# -11 29 11      #group catchabilities
  -1 60 1      #group catchabilities to prevent weirdness (averages ?)
  -2 60 2      #group catchabilities
  -3 60 3      #group catchabilities
  -4 60 4      #group catchabilities
  -5 60 5      #group catchabilities
  -6 60 6      #group catchabilities
  -7 60 2      #group catchabilities
  -8 60 7      #group catchabilities
  -9 60 8      #group catchabilities
  -10 60 9      #group catchabilities
  -11 60 10      #group catchabilities
  2 107 100       # turn on exploitation rate target
  2 108 10        # set exploitation rate target as x% (Catch(numbers) over Rec(N)
PHASE1
fi
# ---------
#   PHASE 2
# ---------
if [ ! -f 02.par ]; then
mfclo32May2808  swo2007A12F11003.frq 01.par 02.par -file - <<PHASE2
  #-999 49 10         # LF ESS reweighting by factor of 1 over n
  #-999 50 10         # massF ESS reweighting
  1 189 1         # write length.fit and weight.fit (obs. and pred. LF data)
  1 190 1         # write plot.rep
  1 149 500       # set penalty on recruitment devs to n over 10 (500 over 10 ~ cv of 0.1)
  1 1 400         # set max. number of function evaluations per phase
  1 50 0         # set convergence criterion to 1E+0
  1 12 0         # attempt to shut off mean first length growth estimation
  1 13 0         # attempt to shut off mean last length growth estimation
  1 14 0         # attempt to shut off k growth estimation
PHASE2
fi
# ---------
#   PHASE 3
# ---------
if [ ! -f 03.par ]; then
mfclo32May2808  swo2007A12F11003.frq 02.par 03.par -file - <<PHASE3
# 2 70 1         # activate parameters and turn on (recruitment time series variability among regions?)
# 2 71 1         # estimation of temporal changes in recruitment distribution (related to above)
  2 70 0         # dk attempt to turn off recruitment time series variability among regions?)
  2 71 0         # dk attempt to turn off recruitment distribution (related to above)
  2 110 5         # penalty weight for rec deviations (related to above)
PHASE3
fi
# ---------
#   PHASE 4
# ---------
if [ ! -f 04.par ]; then
mfclo32May2808  swo2007A12F11003.frq 03.par 04.par -file - <<PHASE4
  2 68 0         # de-activate? estimate movement coefficients #manual says activates movement
  2 69 0         # de-activate? sets generic movement option (now default) #manual says estimates movement
params
# 2 68 1         # estimate movement coefficients #manual says activates movement
# 2 69 1         # sets generic movement option (now default) #manual says estimates movement params
  -999 48 1       # activate selectivity estimation
PHASE4
fi
# ---------
```

```
#   PHASE 5
#  ---------
if [ ! -f 05.par ]; then
mfclo32May2808  swo2007A12F11003.frq 04.par 05.par -file - <<PHASE5
  1 16 0          # estimate length dependent SD (I3=1)
  -999 27 1       # estimate seasonal catchability for all fisheries
PHASE5
fi
#  ---------
#   PHASE 6
#  ---------
if [ ! -f 06.par ]; then
mfclo32May2808  swo2007A12F11003.frq  05.par 06.par -file - <<PHASE6
###  1 14 1         # estimate K
  1 141 0        # sets likelihood function for LF data to mod chi2
  -1 13 -1       # effort dev weighting (neg = sqrt transformed)
#switch relative weighting of Aus/NZ vs Jpn CPUE
#UA1 ###:   -2 13 50       # effort dev weighting (neg = sqrt transformed)
#UAJ ###:   -2 13 8       # effort dev weighting (neg = sqrt transformed)
#UJA ###:   -2 13 50       # effort dev weighting (neg = sqrt transformed)
  -3 13 -1       # effort dev weighting (neg = sqrt transformed)
#UA1 ###:  -4 13 50       # effort dev weighting (neg = sqrt transformed)
#UAJ ###:  -4 13 50       # effort dev weighting (neg = sqrt transformed)
#UJA ###:  -4 13 8       # effort dev weighting (neg = sqrt transformed)
  -5 13 -1       # effort dev weighting (neg = sqrt transformed)
  -6 13 -1       # effort dev weighting (neg = sqrt transformed) 100 over 10 = CV 0.15
#UA1 ###:  -7 13 50       # effort dev weighting (neg = sqrt transformed)
#UAJ ###:  -7 13 8       # effort dev weighting (neg = sqrt transformed)
#UJA ###:  -7 13 50       # effort dev weighting (neg = sqrt transformed)
  -8 13  -1       # effort dev weighting (neg = sqrt transformed)
  -9 13  -1       # effort dev weighting (neg = sqrt transformed)
  -10 13 -1       # effort dev weighting (neg = sqrt transformed)
#UA1 ###:  -11 13 50       # effort dev weighting (neg = sqrt transformed)
#UAJ ###:  -11 13 50       # effort dev weighting (neg = sqrt transformed)
#UJA ###:  -11 13 8       # effort dev weighting (neg = sqrt transformed)
 -1 16 0  #selectivity flexible with age =0
 -2 16 0
 -3 16 0
 -4 16 0
 -5 16 0
 -6 16 0
 -7 16 0
#switch selectivity on southern area free or non-decreasing with age
#SF ###:   -8 16 0  #selectivity non-decreasing with age =1
#SM ###:   -8 16 1  #selectivity non-decreasing with age =1
 -9 16 0
 -10 16 0
 -11 16 0
#-999 16 0
PHASE6
fi
#  ---------
#   PHASE 7
#  ---------
if [ ! -f 07.par ]; then
mfclo32May2808  swo2007A12F11003.frq 06.par 07.par -file - <<PHASE7
# steepness should be fixed...
  2 145 1        # estimate Beverton Holt SRR with small penalty
  2 146 1        # SRR parameter active
  2 147 0        # recruitment lag is 0 quarters (this was 1 in 2006...confirm implications)
  2 148 4        # base F is average over last 24 quarters (MSY stuff) (was 24)
  2 155 0        # base F average does not include last 4 quarters  (MSY stuff) was 4)
#  2 153 9000      # parameters of beta distribution defining prior for
#  2 154 1000      # steepness - mode = (153 flag  over (153 flag + 154 flag), sd approaches 0 as flags get big
# beta priors ignored - fixed in .inpar
PHASE7
fi
```

```
# ---------
#  PHASE 8
# ---------
if [ ! -f 08.par ]; then
mfclo32May2808  swo2007A12F11003.frq 07.par 08.par -file - <<PHASE8
  2 107 0       # off- turn on exploitation rate target
  2 108 0       # off- set exploitation rate target as x% (Catch(numbers) over Rec(N)
#not sure which of 145/149 below takes precedence - set both
#switch SRDevs
#switch SRDevs
#r5 ###: 1 149 2       # set penalty on recruitment devs to n over 10 (500 over 10 ~ cv of 0.1; 14 over 10 ~ 0.6;
31~0.4)
#r5 ###: 2 145 20      # set penalty on SR devs to n (seemingly not n over 10) (500 over 10 ~ cv of 0.1; 14 over 10
~ 0.6; 31~0.4)
#r1 ###: 1 149 50      # set penalty on recruitment devs to n over 10 (500 over 10 ~ cv of 0.1; 14 over 10 ~ 0.6;
31~0.4)
#r1 ###: 2 145 500     # set penalty on SR devs to n (seemingly not n over 10) (500 over 10 ~ cv of 0.1; 14 over 10
~ 0.6; 31~0.4)
  2 113 0        # shut off estimate initpop over totpop scaling parameter
  1 1 750        # set no. function evaluations
  1 50 -3        # set convergence criterion to 1En
PHASE8
fi
# ---------
#  PHASE 9
# ---------
if [ ! -f 09.par ]; then
mfclo32May2808  swo2007A12F11003.frq 08.par 09.par -file - <<PHASE9
# estimation of negative binomial parameter a
### -999 43 1        # estimate a for all fisheries
#  1 183 20       # change recruitment CV for first I3 time intervals (or years - test)
#  -100001 1 1000  # constrain rec in all regions by I3 over 10 ???
#  -100001 2 1000  # constrain rec in all regions by I3 ???
#  -100001 3 1000  # constrain rec in all regions by I3 ???
#  -100001 4 1000  # constrain rec in all regions by I3 ???
#  -100001 5 1000  # constrain rec in all regions by I3 ???
#-999 49 5 -999 50 5
#-999 49 20 -999 50 20
#switch CLM Effective sample sizes
#ES05 ###: -999 49 5 -999 50 5
#ES20 ###: -999 49 20 -999 50 20
PHASE9
fi
# ---------
#  PHASE 10
# ---------
if [ ! -f 10.par ]; then
mfclo32May2808  swo2007A12F11003.frq 09.par 10.par -file - <<PHASE10
  1 1 3000       # set no. function evaluations
  1 50 -6        # set convergence criterion to 1En
  -999 55 1      # compute biomass with catchability for all fisheries set to 0
PHASE10
fi
# ---------
#  PHASE 11
# ---------
#if [ ! -f 11.par ]; then
#mfclo32May2808  swo2007A12F11003.frq 10.par 11.par -file - <<PHASE11
#  1 145 3       # set output level 3 for Hessian calc
#PHASE11
#fi
#scenario switch ###: cp 10.par ../crossB/ ###:.outpar
#scenario switch ###: cp plot-10.par.rep ../crossB/ ###:.rep
#scenario switch ###: cp plotq0-10.par.rep ../crossB/ ###:.q0.rep
#scenario switch ###: cp length.fit ../crossB/ ###:length.fit
#scenario switch ###: cp weight.fit ../crossB/ ###:mass.fit
#scenario switch ###: #cp *.hes ../crossB/ ###:.outHes
```

```
#scenario switch ###: #cp *.var ../crossB/ ###:.outVar
#
#scenario switch ###: mv 10.par  ###:.outpar
#scenario switch ###: mv plot-10.par.rep  ###:.rep
#scenario switch ###: mv plotq0-10.par.rep  ###:.q0.rep
#scenario switch ###: mv length.fit  ###:length.fit
#scenario switch ###: mv weight.fit  ###:mass.fit
#scenario switch ###: #mv *.hes  ###:.outHes
#scenario switch ###: #mv *.var  ###:.outVar
```