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**A MULTIFAN-CL STOCK ASSESSMENT FOR  
SOUTH-WEST PACIFIC SWORDFISH 1952-2004**

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## **Executive Summary**

This paper describes a stock assessment for broadbill swordfish (*Xiphias gladius*) in the South-West Pacific Ocean (0-50S, 140E-175W) for the period 1952-2004. Swordfish have been exploited in this region primarily as by-catch in the Japanese longline tuna fisheries since the 1950s. Total catches and catch rates remained fairly consistent from about 1970-1996, at which time Japanese catches began a steady decline. Australian and New Zealand catches increased at this time, such that annual catches in 1997-2004 were roughly double the levels in the preceding period. In the mid-1990s, the Australian fleet gradually expanded offshore with some of the fleet specifically targeting swordfish. During this period, declining catch rates and declining size composition in core areas of the fishery have raised concerns about the sustainability of the population. This assessment attempts to integrate the available fisheries data on total catch, catch rates, and size composition with biological studies on age, growth, reproductive dynamics and stock structure, to provide a summary of the current stock status, and likely implications of future harvesting. Multifan-CL software was used as the primary assessment tool, with which to formulate alternative age-structured, spatially-disaggregated models of the regional population dynamics. We recognize that the available data are probably not very informative with respect to many key processes that affect the population resilience (e.g. stock recruitment productivity and natural mortality) and the stock status estimates are sensitive to many of the arbitrary assumptions imposed in the modelling process. We attempted to explicitly admit this problem by placing a heavy emphasis on exploring model uncertainty (as opposed to parameter uncertainty estimated conditional on any specific model being correct), with results from more than 500 model specifications explored. The likelihood-based objective function does not provide a sufficient basis for comparing models in this context, so we defined additional plausibility criteria that inevitably include an element of subjectivity. The plausibility criteria include similar terms to the objective function (related to the quality of the fit between model predictions and observations), but also include additional terms related to numerical performance and agreement with pre-conceived notions of stock dynamics. This process represents an attempt to formally articulate the types of subjective decisions usually considered in model selection, and leads to the conclusion that multiple models are plausibly consistent with the data. We consider the key features of the most reliable data to be described well by many models, but all models also suggest some problems in model formulation (or our interpretation of data). The stock status summary represents a synthesis of the Maximum Posterior Density (MPD, or best point estimates) results from a subset of 10 models (the most plausible ensemble), from which we reach the following conclusions (note in the following that the estimates represent the median (and range) of the MPD results from the plausible model ensemble, such that if one of the models at the extreme end of the range were actually a perfect unbiased estimator, there would be a 50% chance of the true value being more extreme than the uncertainty bound indicates):

1. We consider the relative Total Stock Biomass (TSB) 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. The MPD results from the plausible model ensemble indicate:
  - $TSB(2004)/TSB(1995)$  median = 0.70, range = (0.56 – 0.74).

2. All of the Spawning Stock Biomass (SSB – roughly corresponding to age 10+ fish) reference points are much more uncertain than TSB because SSB represents a small portion of the catch, and may be badly biased by natural mortality assumptions, and the model aggregation of sex-specific characteristics of growth, mortality and migration. Furthermore, the southern range of the stock seems to consist predominantly of mature females, but this region is poorly sampled by the fishery and it is difficult to relate abundance in this southern part of the population to the core population.
  - $SSB(2004)/SSB(1995) = 0.75 (0.51 - 0.86)$ .
3. The ratio of current biomass over the estimated biomass that would have been observed in the absence of fishing (NF) 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).
  - $TSB(2004) / TSB_{NF}(2004) = 0.59 (0.31 - 0.69)$
  - $SSB(2004) / SSB_{NF}(2004) = 0.49 (0.15 - 0.65)$ .
4. 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 seriously 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 probably above levels that would sustain MSY and fishing mortality is probably below  $F(MSY)$ .
  - $TSB(2004)/TSB(MSY) = 1.7 (0.87 - 3.0)$
  - $SSB(2004)/SSB(MSY) = 3.4 (0.75 - 6.4)$
  - $F(2004)/F(MSY) = 0.70 (0.33 - 2.2)$ .
5. The apparent optimism of the MSY-related reference points is countered by the stock projections (assuming constant future recruitment according to the estimated stock recruitment relationships, and constant effort at 2004 levels), which suggest biomass declines over the short term:
  - $TSB(2009) / TSB(2004) = 0.88 (0.78 - 1.00)$
  - $SSB(2009) / SSB(2004) = 0.84 (0.71 - 0.86)$

Despite the emphasis on model uncertainty, there remain a number of assumptions which probably influence these conclusions and remain largely beyond the scope of this assessment, including: 1) catchability of the fleets may be changing in ways that cannot be reliably estimated through the catch rate standardization methods employed, 2) the link between our operational definition of the SW Pacific model domain, and the broader Pacific (and possibly Indian Oceans) is unclear, and 3) all of these models ignore sex-specific population characteristics (natural mortality, growth and migration), which may contribute to potential biases in estimators. The likely implications of these issues are discussed in general terms, and we provide some suggestions as to how the assessment might be improved in future iterations. However, we expect that the assessment uncertainty will not be substantially reduced until there is considerable additional data collected, ideally including improved

interpretation of catch rates, direct observations of movement from tagging (conventional, electronic or genetic), direct ageing from hard parts, and improved size and sex sampling. We suggest that the most productive means of acting on the advice resulting from the assessment process will probably be related to testing and adopting management strategies that include feedback decision rules that are robust to the identified assessment uncertainties to the extent possible. In this manner, we support the recent initiative of the Australian Department of Agriculture Fisheries and Forestry to develop harvest strategies for all commonwealth fisheries, and encourage a similar, multilateral approach for the straddling and migratory stocks of the WCPO, including swordfish.

## **Introduction**

The broadbill swordfish (*Xiphias gladius*) population in the South-West Pacific has been routinely assessed using data-based indicators in the region of the Australian Eastern Tuna and Billfish (ETBF) fishery for several years (e.g. Campbell 2005). The offshore expansion of the ETBF fleet in response to declining inshore catch rates (Campbell and Hobday 2003) in recent years has raised concerns about the economic and biological sustainability of the ETBF, and provided the impetus for this formal model-based assessment. The preliminary exploration was presented to the WCPFC Scientific Committee in 2005 (Kolody et al 2005). This paper represents an extension of that work, with several methodological improvements and an emphasis on a systematic search for alternative models that are plausibly consistent with the available data. We provide an ad hoc synthesis of the results from a range of models and report against common reference points with an attempt to identify which are considered to be the most reliably estimated. Future assessment improvements are discussed.

## **History of the SW Pacific swordfish fishery**

We have defined the SW Pacific swordfish fishery as the region bounded by 0 - 50S and 140E - 175 W (Figure 1, Figure 2) using the reasoning defined in the subsequent section. The distant water Japanese longline fleet has recorded swordfish catches in the SW Pacific region since 1952 (Figure 3). The Japanese catches increased steadily until the early 1970s, then remained fairly constant (substantial interannual fluctuations around a steady mean) until 1997, at which time the Japanese fleet was denied access to Australian and New Zealand territorial waters. Swordfish were generally considered a by-catch species until the late 1990s (though it was always valuable and presumably pursued opportunistically to some degree). Beginning around 1997, swordfish became a main target species in Australia, and the New Zealand fishery seemed to undergo a similar development (despite the ostensible by-catch nature of the fishery until recent quotas were introduced). The total Japanese catch has declined steadily since 1997, while Australian and New Zealand catches increased dramatically. The Australian expansion was accompanied by a progressive offshore movement of the fleet (Campbell 2002). The catch of Pacific Island Nations has also increased in recent years, but remains a small portion of the total. Catch in numbers from about 1997-2002 have been roughly double the mean of the 1970-96 period. Total catches in Australia and New Zealand have dropped considerably in the last two years (partly in response to changing economic conditions). 2004 was the first year that the Spanish fleet reported swordfish catches in the SW Pacific, as part of an exploratory fishing program.

The South-Central Pacific, defined here as the southern hemisphere WCPFC convention area other than the SW Pacific (Figure 2, region 6) shows an even more rapid increase in catch than the SW Pacific region. This is primarily due to Korean and Taiwanese fleets (Figure 3). The relationship between the population dynamics of the South-West and South-Central Pacific is potentially important, but for reasons discussed in the following section, we do not include the South-Central region in this assessment.

## ***Spatial Considerations in the Assessment***

### **The SW Pacific population**

Swordfish are one of the most widely distributed pelagic species, observed from 50N-50S in the Pacific and at all longitudes. 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, Far Seas Fisheries 1985) tend to be offset from these high density areas, in tropical Western and Central regions of the Pacific. 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. Swordfish tagging has not been conducted on a significant scale in the Pacific Ocean, and most of our movement inferences are indirect. Genetic studies indicate that there is not uniform gene flow among the Pacific 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 (and the SW Pacific indistinguishable from the eastern Indian Ocean). We chose a pragmatic stock definition for this assessment that focuses on the worrying trends in the Australian and New Zealand fisheries and assumes the SW Pacific is effectively an isolated unit.

The North-South boundary for the assessment is easily justified on the basis of the genetic structure, while we assume that the Australian continent represents a reasonable western boundary for the stock. The 175 W eastern bound is more difficult to justify. There are substantial catches of swordfish east of 175 W (Area 6), but these catches tend to be in more equatorial waters, and not contiguous with the high catch and CPUE regions of the SW Pacific. Expanding the model domain to encompass the South-Central region would lead to two problems. First, the central South Pacific region is contiguous with high catch and CPUE regions immediately to the North and East of the defined Area 6. This would represent a less satisfactory break than the one adopted, and leads to an argument for further expansion into the northern hemisphere and beyond the eastern bounds of the WCPFC convention area. Second, CPUE in the South-Central region is based only on the DWF fleets, for which we currently do not have detailed data for standardization. The nominal CPUE series in this region indicates an increasing trend (Figure 5) that is generally opposite of that observed in the SW Pacific region. This might indicate an increase in swordfish targeting rather than increasing abundance, perhaps in the manner experienced by Australian and New Zealand fleets in the 1990s. This is an issue revisited in subsequent sections in relation to the increasing CPUE trends by the Japanese fleet in Area 1.

### **Spatial Structure within the SW Pacific**

Within the SW Pacific, we have opted for a spatially disaggregated assessment structure for two main reasons. First, there is obvious spatial heterogeneity in both the fishing fleets and swordfish population characteristics. There is no consistently reliable index of abundance (standardized CPUE) spanning the whole region and time of interest. Unlike many of the pelagic fisheries assessments in the WCPO, we have less confidence in the widespread Japanese longline CPUE series relative to other localized series (Australian and New Zealand), for which we have more detailed



understanding of fishing practices and better data for catch rate standardization. Furthermore, there seems to be a distinct partitioning of the population, with only very large (predominantly female) fish in the southern part of the range where they are mostly taken as by-catch in Southern Bluefin Tuna (SBT) fisheries. There is also a seasonal component to all of the CPUE series (but particularly the southern fleets). If a single abundance index for the region were to be calculated, it would represent a patchwork of spatial and temporal assumptions to stitch together CPUE from the various fleets. Retaining the distinct spatial structure of the different series maintains the focus on the explicit assumptions involved in translating from local to regional abundance estimates. The second reason for using spatial structure relates to the type of advice that might be provided. Part of the impetus for the assessment was driven by the apparent localized depletions, and this cannot be described in the context of localized changes in abundance if the population is modelled as an aggregate unit. When nations consider the merits of different management initiatives in a unilateral or multilateral context, it would be preferable to understand how adjacent fisheries affect the region of interest. While we consider these to be sound reasons for desiring a spatially-disaggregated assessment, we also recognize that it is not clear that the current analytical methods, and conceptual understanding of spatial dynamics are sufficient to resolve the types of spatial questions that we seek to answer given the available data.

The spatial structure defined for stock assessment purposes represents a trade-off between competing objectives. We want to partition the population into relatively homogenous units to prevent statistical biases caused by aggregating heterogeneous units, but we also need to maintain a structure that is simple enough to formulate computationally tractable estimators. The preliminary assessment (Kolody et al 2005) contained 7 areas, and suffered from dubious source/sink migration dynamics. It is likely that there was a mismatch between the number of spatial links and the iteration timestep (quarterly), such that seasonal migrations could not be properly described. The revised spatial structure (Figure 2, regions 1-5) has a maximum distance of two links between regions and seems to resolve the source/sink problem. The revised structure is also expanded 5 degrees eastward to encompass a high CPUE region immediately Eastward of the previously defined NZ fishery.

Each of the 5 areas approximately encapsulates some more or less distinct component of the fishery (Figure 4). The main Australian longline fleet operates in region 2, with the larger dedicated swordfish vessels frequently venturing further offshore to area 3. The New Zealand domestic fishery operates primarily in area 4. The Japanese fleet has operated in all areas historically, but catches have dropped considerably over the last 10 years, with negligible recent catches in Areas 2 and 4. The southern Japanese and NZ charter fleets (area 5) are primarily targeting SBT. In terms of the biological characteristics of the population, spawning seems to occur primarily in area 2 (though some larvae have been found in more eastern tropical waters), and the swordfish caught in the SBT fishery exhibit distinct size frequency distributions, consisting primarily of very large females.

### **Migration dynamics: stock structure, mixing rates and site fidelity**

A further consideration of the spatial dynamics of swordfish arises in relation to the manner of the mixing of the stock. If the assumption of a single spawning stock is

essentially correct for the SW Pacific region defined, we have found it useful to think about a further dichotomy in the migration dynamics: the homogenous-mixing population, and the foraging site fidelity population, with the difference illustrated schematically in Figure 6. The homogenous population refers to a spatial structure in which all individuals in a given region (of the same age and sex) have the same probability of migrating to another region irrespective of their prior experience. The foraging site fidelity model assumes that fish that recruit to a particular region tend to remain in that region, leaving to spawn, but then returning to the same foraging site. The most extreme foraging site fidelity could arise from multiple distinct stocks, while less extreme versions might be represented by sub-populations that mix on the spawning grounds, and have linked recruitment processes. The sub-populations could be established by many processes, including chance (larval drift), or more predictable life history characteristics (sex or size-based regional preferences). The homogenous population is most commonly assumed in pelagic fisheries models. However, during our initial explorations of the SW Pacific assessment, (including the parameterization of operating models for simulation testing), we found it difficult to reconcile both seasonal migration and localized depletion within a homogenous mixing population. This provided the impetus to explore foraging site fidelity parameterizations (using CASAL and spatially structured production models).

Which representation is closer to reality, and whether it matters for management purposes in the SW Pacific is not clear. However, the updated standardized catch rates in the revised 2006 spatial structure seem to suggest that the variation in catch rates among sub-regions is less extreme than we had previously thought, and either representation seems to be capable of providing a representation of the population that is consistent with the available data.

## **Data**

### **Catch in Numbers**

Swordfish are caught almost exclusively by commercial longliners and reported in log books in numbers. Reported catches in purse seiners (Bailey et al 1996), and recreational fisheries have been negligible. Figure 4 illustrates the catch history from the major fleets by area over the assessment period 1952-2004. Australian, Japanese, New Zealand and Spanish data were obtained from the source nations; Secretariat of the Pacific Community provided data for Korean, Taiwanese and Pacific Island Nations fleets.

### **Fishing Effort and Catch Rates**

Interpretation of SW Pacific catch rates has been a prime focus of the data-based assessment program conducted in Australia for many years. Campbell (2005) provides a description of the standardization methodology used for the Australian, Japanese and New Zealand fleets adopted for the assessment. Unwin et al (2005) provides additional information on the New Zealand CPUE characteristics.

Relative abundance indices are generally the next most important input to stock assessment after the catch history. For most pelagic fisheries, this consists of standardized commercial catch rates interpreted under the usual assumption that CPUE is proportional to abundance (or some other quantifiable relationship exists

between effort, fishing mortality and abundance). There are some serious problems generating reliable abundance indices from swordfish CPUE series. None of the fleets have consistent coverage of the SW Pacific region for the entire history of the fishery. For most of the history of the Japanese fishery, swordfish have been caught as by-catch, presumably with opportunistic targeting under favourable conditions. As Australian and New Zealand fleets began targeting swordfish in the mid-1990s, their catch rates increased manyfold. Much of this can be explained by the adoption of easily identified practices including night sets and light sticks, which show up as powerful predictors in GLM-based catch rate standardization. We consider the Australian Mooloolaba grounds fishery (areas 2 and 3) during the 1997-2004 period to provide the most consistently reliable relative abundance indices in the region. Effort data from the Australian fleets prior to 1997 (and NZ prior to 1998) were removed from the analysis, because we are not confident that standardization procedures can account for all of the important factors that affected increasing catchability during this period of rapid learning. All of the Australian and the New Zealand domestic standardized CPUE series show similar declining trends (Figure 7) over the latter period.

Fine-scale (1x1 degree) effort data was used for the Japanese catch rate standardization 1971-2003). The resolution of data available prior to 1971 is much more coarse (5x5 degree), lacks the data on set depth information (hooks per basket) and shows some discrepancies with the 1x1 data when the standardized series are compared, so we opted to set these data to missing in the Multifan-CL analyses. Even the fine scale standardized catch rates are highly variable for most of the history (Figure 8). The mean pattern is rather flat from about 1971-90, and the recent declining trends in the core areas (2-4) (Figure 7) actually closely resemble the Aus and NZ trends. Figure 9 illustrates the similarity in Japanese and Australian trends in the time/area of overlap that is evident when the seasonality is removed. This similarity gives us confidence that a similar trend is being observed inside and outside of the Australian EEZ, and if catchability is changing in the two fleets in a manner that cannot be identified in the standardization process, then both fleets must be changing in a very similar manner. In contrast to the core area, the recent trend in the tropical region (Area 1) might be interpreted as flat or even increasing over the last few years. This could indicate that the population or fleet catchability characteristics in this region are more closely related to the South-Central Pacific (Figure 5) than the SW Pacific.

### **Catch-at-size**

Extensive and reliable size sampling data have been collected from the Australian longline fleet since 1997. This data pertains to individual trunked weights being collected from processors, with the sample covering ~75% of all swordfish landed. However, only a subset of this data can be directly allocated to specific fishery regions. Japanese size frequency data is available since 1971 but data was collected intermittently resulting in many years with no sampling (additional data collected prior to 1960 has recently been obtained from published reports, but this has not been included in the assessment). From around 1980 to 1997 observers on Japanese vessels operating in the Australian EEZ provided considerable additional size data for this fleet, and the two data series have been merged into a single time series in the regions of overlap. Japanese size data is aggregated into spatial units that do not align with our regional structure, and some mis-allocation by region will have occurred as a

result. The New Zealand observer program provides excellent size frequency data for the NZ charter fleet which primarily targets SBT (but this accounts for about 1% of NZ catch); size frequency sampling from the NZ domestic fishery is much lower. Several hundred Pacific Island Nation (PIN) samples have also been collected in recent years.

The time series of mass and length sample sizes for the individual fleets used in the assessment are illustrated in Figure 10. Various conversion factors had to be applied to get standard mass and length units across fisheries. For all assessment calculations, we have adopted post-orbital fork length and trunked mass as the standard. Given the bewildering variety of length measurements in use for billfishes, it is likely that some discrepancies in units are embedded in these data.

## **Tags**

There have been relatively few swordfish tagged in this region, with recapture rates of around 1-2 %. To date, the results from pop-up satellite tags, and recovery of conventional tags from combined scientific and recreational programs number less than 10. None of them provide evidence of large-scale movements (more than a couple hundred km), although direct evidence of large movements have been seen in other populations (e.g. Sedberry and Loefer 2001). Tagging data are not used in the assessment.

## **Biological Parameters**

A number of directed research studies have been undertaken to study the biological characteristics of swordfish in the SW Pacific. These are cited under the relevant section under Model Assumptions below.

## **Assessment Models**

Multifan-CL was adopted as the primary software for the assessment because of the rich feature set available 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 assessment modeling framework initially developed and routinely applied to the assessment of tuna species of the Western and Central Pacific Ocean (e.g. Kleiber and Yokawa 2002 present a North Pacific swordfish assessment). Most technical specifications of Multifan-CL are documented in Kleiber et al 2005. A script file listing control specifications for the swordfish analysis is included in Appendix 1. While the results seem broadly consistent with our intuition, there is a black box element to Multifan-CL, in that the implementation of a number of features was not consistent with expectations, and it is likely that additional undocumented features were not recognized. Given our emphasis on model uncertainty, the effects of unrecognized features are probably less important than if we opted to adopt a single best model as the basis of the assessment.

This assessment was initially identified as a useful candidate for comparing alternative model formulations. CASAL (Bull et al 2003) estimators are currently being developed in parallel, and are described in Davies (2006) for comparison. A spatially-disaggregated Pella-Tomlinson (age-aggregated) production model (SDPT) was also explored, as an independent comparison for the Multifan-CL results, but also

to compare alternative migration assumptions (i.e. the homogenous mixing and foraging site fidelity models). Key reference points for the the Multifan-CL and SDPT results were broadly similar when the models were constrained by similar life history considerations. Given the similarities, and the fact that Multifan-CL explicitly describes transient age structure effects and admits size frequency data, there was not much justification for pursuing the SDPT models further.

## **Comments on Parameter Estimation**

Using the batch processing script in Appendix 1, Multifan-CL completes a full minimization in approximately 60 minutes using a 3 GHz Pentium PC. We found the minimization to be reliable for the majority of options described in this paper. However, given the number of models explored, we did not routinely test whether local minima were being identified, and concluded that if the minimum plausibility criteria (defined subsequently) were met, the result would be informative whether it was a local or global minimum.

As applied in this assessment, a typical model configuration had about 1700 parameters, most of which were effective effort deviations (essentially equivalent to CPUE observation errors). Key parameters estimated that define the stock dynamics include:

- Fishery selectivity
- Fishery catchability
- Annual recruitment deviations (from the stock recruitment curve)
- Initial population structure
- Migration co-efficients

Other key parameters were tightly constrained by priors so as to be essentially fixed (though with a range of alternatives tested in some cases as detailed below:

- Natural mortality
- Stock recruitment curve

Objective function terms relating directly to the data included the total catch, effort deviations (CPUE fit), and Catch-at-length/mass. The form of the likelihood terms and additional priors and constraining assumptions are listed in the following section.

## **Model Assumptions**

This section describes the assumptions underpinning the stock assessment models. A number of the categories describe multiple alternative assumptions, which relate to the exploration of model uncertainty as explained in the next section.

## **Fishery Definitions**

The SW Pacific was divided into 10 fisheries as listed in Table 1, each operating in one of the 5 spatial regions. Visual inspection of the available size frequency data in overlapping/adjacent regions suggested that PIN fleets are catching similar sized fish to the Japanese fleets, and these fleets were aggregated with the other DWF fleets to keep the number of fisheries to a reasonable level. After the aggregation, the

Japanese effort series was rescaled so as to recover the original CPUE series (i.e.  $\text{Effort}(\text{after aggregation}) = \text{Effort}(\text{Jpn}) \times \text{Catch}(\text{after aggregation}) / \text{Catch}(\text{Jpn})$ ).

## **Time period**

The models were iterated on a quarterly timestep, 1952-2004, plus an additional 5 years of projections assuming that all effort remained constant at 2004 levels (including the seasonal variability). In Multifan-CL, projections consist of extending the time series with an assumed future effort (or catch) trajectory, and the model estimates the corresponding catch (or effort) that corresponds to the provided values (with deterministic future recruitment driven by the stock recruitment relationship).

## **Age and Sex Structure**

The modeled population consisted of 40 quarterly age classes (0-19+ in years;), but sexes were combined.

## **Age and Size**

The age-length relationship for swordfish is generally thought to be sexually dimorphic, and we adopted a growth curve intermediate between the male and female curves described in Young and Drake (2004) (Figure 12). The variance about the mean growth curve was also inflated to the value of the males and females combined. The mean and variance relationships were assumed known in the analyses. The length-mass relationship was estimated from observer data, and based on post-orbital fork lengths (cm) and trunked mass (kg):  $\text{mass} = 0.0000214(\text{length})^{2.902}$ .

## **Maturity and the Spawning Stock**

Males and females appear to reach sexual maturity at different ages (and sizes) (Young and Drake 2002), and we assumed that the female maturity schedule would be the most appropriate approximation for spawning biomass calculations (Figure 12). As far as we know, the majority of swordfish spawning in the SW Pacific occurs in the Coral Sea off of NE Australia. Multifan-CL assumes that all of the spawning stock contributes to each spawning event, regardless of the spatial location. This approximation would only be problematic if 1) there is a strong relationship between spawning biomass and recruitment, and 2) the proportion of spawners in the spawning area varies from year to year.

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

Catch rates are assumed to be highly informative relative abundance indices (effort deviation prior CV ~ 0.15) for the 3 Aus fleets (1997-2004) and the NZ domestic fleet (1998-2004). We have observed in simulations that these models tend to perform poorly if there is no reliable relative abundance index, and it follows that we would also expect poor performance if the index is poorly fit (whether or not it is reliable). Thus we consider a good fit to the CPUE data to be an essential requirement for a reliable assessment (but not a sufficient requirement) and justifies the low CV. CPUE is assumed to be relatively uninformative (CV ~ 0.7) for the Japanese fleets (1971-

2003). Since the catches of the other DWF and PIN fleets were merged into the Japanese fleet, the effort observations from the aggregate fleets were re-scaled so that the original Japanese CPUE series was maintained. Effort in years outside of the periods defined above was set to missing and thus should not have any influence on the estimated population dynamics.

In addition to the role that CPUE plays as a relative abundance index within a region, the assumed catchability also influences the relative abundance implications among regions. It is common to assume that the catchability for a given fleet is the same in different regions, and hence provides a measure of relative density across regions. In this case, we have assumed two catchability groupings:

- Aus and NZ domestic fleets
- Japanese fleets

These assumptions are most questionable in the southern area (5). While we are reasonably satisfied that the catchability for fisheries 6-7 (core Australian fisheries) should be similar to 8 (southern Aus), it is not clear that fishery 8 abundance is representative of fisheries 5 and 10 because of the different nature of the SBT by-catch fisheries, different catch size composition, and the different regions of operation within Area 5. It is also not clear that the catchability from fleets 1-4 should be equivalent to fishery 5 because of the different operational characteristics of the fleets which we are interpreting as different selectivities. Table 2 illustrates the ratio of the standardized catch rates among fleets in overlapping regions for recent years. The Aus and NZ core area fleets all have a similar ratio to the Jpn fleets in A2-4, but there is a discrepancy of a factor of 2 in Area 5. Relaxing the Area 5 catchability constraint often led to a bizarre distribution of fish among areas in some exploratory cases (e.g. Area 5 containing half of the total population). We decided to leave this constraint in for pragmatic purposes, but recognize that it should be revisited in the future.

The equal catchability constraint implies that the same CPUE in two different regions corresponds to an equivalent density (fish per unit volume) between areas. The actual volume (or surface area of the region) is required to interpret the density as relative abundance (i.e. all other things being equal, double the area corresponds to double the abundance). However, calculating what the effective area of a region is can be very problematic when the spatial and temporal distribution of fishing effort changes over time, and assumptions about fish density in unfished areas can lead to lengthy philosophical debates. As a first attempt at admitting that the model might be sensitive to these effective area assumptions, we included three options in the model uncertainty grid (Table 4):

- geographical area: the approximate surface area of water on the map as defined in Figure 2 (adjusted for the earth's curvature)
- Japanese fished area: the maximum number of 1 X 1 degree squares within an area fished by the Japanese fleet during any year from 1971-2003.
- Swordfish caught: as the Japanese fished area, except only including squares in which the swordfish catch was greater than 0.

The relative areas are listed in Table 3. All of the assumptions could be seriously flawed, and this might merit further deliberation in future iterations of the assessment.

## Natural Mortality

There is a paucity of data providing direct information about swordfish mortality (e.g. from tagging), and we know that simulation testing of integrated stock assessment models, that  $M$  estimates can be badly biased (e.g. Kolody et al 2004, Sibert 2004). We attempted to test a plausible range of  $M$  options on the basis of life history considerations and observations of the oldest caught individuals. The four options (Figure 19), in the model uncertainty grid (Table 4) included (mean over ages 0-19):

- Low (mean 0.16, exponential decrease with age)
- High (mean 0.26, exponential decrease with age)
- Low (mean 0.24, exponential decrease plus spawning-related mortality)
- High (mean 0.41, exponential decrease plus spawning-related mortality)

The lowest mortality assumption approximately corresponds to a central mortality vector adopted in Southern Bluefin Tuna assessments (e.g. Polacheck et al 1998). We would expect this to represent a lower bound on plausibility, as the oldest observed SBT (40+) are estimated to be several years older than the oldest observed swordfish (18 years in SW Pacific, Young and Drake (2004), 25-30 in other oceans). The shape of the SBT curve was determined by a combination of juvenile tagging studies and observed age composition. The high mortality assumption shifts the curve up by an arbitrary amount. The corresponding vectors with spawning-related mortality result from speculation that the metabolic stress of spawning and long distance spawning migration might increase mortality, and add an additional arbitrary mortality term directly proportional to the age-specific maturity ogive.

## Migration

The population is assumed to have homogenous mixing characteristics (all individuals of age  $a$ , in quarter  $q$  and region  $r$ , have equal probability of migrating in a given direction) within areas 1-5, as illustrated in Figure 6, with movement potentially occurring between all adjacent areas. Migration occurs instantaneously at the beginning of each quarter, prior to fishing removals. Quarterly parameters are estimated to describe seasonal movements, and age-specific movement is estimated as a linear function of age. Movements are calculated using the implicit method (Kleiber et al 2005), which provides a stable transition when movement in both directions is high. There is limited control over the specification of migration parameters (i.e. all parameters given an identical prior mode), and we chose the specification of low and high diffusion priors to be one of the dimensions in the model uncertainty grid (both with a weak prior, ln S.D.  $\sim 2.2$ , Table 4).

## Fishery Selectivity

Fishery selectivity is assumed to be constant over time and identical for two groupings:

- Northern: fisheries 1-4,6-9
- Southern: fisheries 5,10

Visual inspection of the available size frequency data did not suggest any obvious reason for partitioning the selectivity among the northern fleets. Ideally, we would have liked to assume that selectivity for the Southern region was also identical to the Northern region, such that the driving factor in the different catch size distributions



would reflect differential migration/availability. However, southern fishery 8 more closely resembles the northern fisheries than fisheries 5 and 10. This might suggest that the boundary of area 5 could have been adjusted to better partition this southern region. But it is also not clear that the available age-specific migration functions in Multifan-CL have sufficient flexibility to spatially segregate mature and immature fish in the desired manner, so the selectivity split is probably a reasonable first approach.

Selectivity was modelled as an age-based process (constrained by the degree of overlap in length among age classes), described by a 5 parameter cubic spline. We considered two options in the model uncertainty grid (Table 4):

- Selectivity non-decreasing with age (SM)
- Selectivity free to increase or decrease as estimated (SF)

The non-decreasing constraint is an approximation for anecdotal reports from the Australian fishery that suggest that the large fish might dominate the catch of a newly fished region for a certain period of time, then gradually be replaced by smaller individuals. This might suggest some sort of behavioural dominance structure in the swordfish population, but this pattern has not been clearly identified in the SW Pacific data (perhaps due to the relatively coarse spatial and temporal scales used for assessment). Given the confounding between gear selectivity, spatial availability and natural mortality, we would not be surprised if the non-decreasing constraint leads to problems in some models.

### **Catch in Numbers Observation Errors**

We assume that the total catches are essentially error free (approximate observation error  $CV \sim 0.07$ ), although it is likely that some additional fishing-related mortality (e.g. discarding of small fish) has been overlooked.

### **Catch-at-Size Sample Characteristics**

Multifan-CL assumes that size-at-age is normally distributed about the mean, and uses a robust likelihood term to reduce the influence of outliers. There are a number of reasons why we might not want to over-fit the size sample data for the swordfish assessment, including: 1) the temporally constant selectivity assumption is probably not valid, particularly in relation to species targeting shifts, 2) the model growth curve is a compromise approximation to the sexually dimorphic reality, 3) many of the small samples are probably not representative of the fleet. We considered 4 down-weighting schemes in the model uncertainty exploration (Table 4):

- Down-weighting factor: 5 (sample size =  $n/5$ )
- Down-weighting factor: 10 (Multifan-CL default)
- Down-weighting factor: 20
- Down-weighting factor: 100

### **Stock Recruitment**

Recruitment was assumed to occur once annually (quarter 1), with the spatial distribution estimated as free parameters (but constant over time). Because of the general difficulty in reliably estimating stock recruitment curves, different levels of

recruitment compensation were implemented in the model uncertainty grid via tightly constrained priors. A Beverton-Holt function was assumed, with 3 steepness ( $h$ ) options (Figure 19, Table 4)

- $h = 0.4$  (fairly unproductive stock)
- $h = 0.65$  (moderate degree of recruitment compensation)
- $h = 0.9$  (high recruitment compensation)

Given the poor data over the majority of the fishery history, and the lack of evidence of highly variable recruitment in the size frequency data, we attempted to constrain the recruitment time series with fairly strong assumptions about the recruitment deviations from the stock recruitment relationship. Two options were adopted in the model uncertainty grid (Table 4)

- recruitment deviation CV  $\sim 0.1$
- recruitment deviation CV  $\sim 0.4$

While the 0.1 constraint seems particularly restrictive, the magnitude of the estimated deviations are generally much more variable than the prior would suggest.

## Initial Population

The initial population structure in 1952 is assumed to be unexploited, but with independent age-specific deviations from mean levels estimated (sizeable deviations from the stock-recruitment curve result in some cases).

## Uncertainty Quantification

Probably all fisheries stock assessment models attempt to make stronger inferences about fish population dynamics than can be justified solely on the basis of the available data, and it is only through the structural and statistical assumptions imposed by the analyst that tractable estimators can be formulated (e.g. Schnute and Richards 2001). Most stock assessments primarily focus on statistical uncertainty quantification (e.g. parameter uncertainty is quantified using bootstrapping, Inverse Hessian – Delta method, or stochastic sampling from Bayesian posteriors and interpreted as though the assumed model structure is fundamentally correct). In addition to the primary model specification, many stock assessments explore a few sensitivity analyses, in which additional models are fit which deviate from the primary specification in one or two dimensions. While the likelihood-based objective function is intended to provide a precise quantitative measure of the degree of agreement between data and observations (and prior expectations), we recognize that there is an inherent risk in interpreting these values literally. The problem stems in part from pragmatic approximations to statistical theory that are required to make tractable estimators, and the unfortunate fact that many assumptions are usually somewhat wrong. Unfortunately, assessment model inferences are usually sensitive to some of the underlying assumptions, such that point estimates may be badly biased and statistical uncertainty intervals, evaluated conditional on the model being correct, tend to be too narrow. Because models tend to be over-parameterized, there is no guarantee that model diagnostics are sufficient to identify a problem on the basis of the agreement between observations and predictions.

The approach taken with the SW Pacific swordfish assessment involved a primary emphasis on model uncertainty, which we have generally found to be greater than the statistical uncertainty conditional on a given model being correct. Toward this end, we defined a set of assumptions that we expected might be important, and refit the model with multiple combinations of these assumptions. Our exploration of what we call model uncertainty here includes elements of statistical uncertainty, in that in some cases we are simply comparing alternative model parameters (e.g. different values of  $M$ ) and we might expect that the objective function provides a perfectly reasonable means of guiding us to the best estimate of  $M$ . Unfortunately, simulation testing has indicated that these estimates can often be badly biased (e.g. Kolody et al 2004, Sibert 2004), and sensitive to other model assumptions that are not comparable on the basis of the objective function. This emphasis on model uncertainty provides some exploration of the (often counterintuitive) interactions among assumptions, and usually leads to the recognition of additional plausible models with potentially different implications for fisheries management. This approach resembles the path taken for Southern Bluefin Tuna (SBT) assessments in recent years (e.g. Polacheck et al 2001) and the parameterization of SBT operating models for management procedure development (e.g. CCSBT 2004).

The assumptions defined in Table 4 were applied in various combinations (Table 6), such that a total of over 500 models were fit in preparing this assessment. Given the automated context in which these model fittings were conducted, it was not practical to inspect the individual model results in the level of detail that would normally be associated with an individual model fitting. In considering whether individual models are plausible we have defined a number of criteria related to numerical convergence, the agreement between model predictions and observations and subjective expectations about stock dynamics. The goodness of fit criteria and some of the prior expectation criteria are analogous to terms in the objective function (except that they are comparable across models), and additional terms related to the plausibility of estimated dynamics are defined (which we could not build into a Multifan-CL assessment without modifying the code). This may seem like a rather subjective process for model selection, but it is no more subjective than the usual exploratory modeling that accompanies an assessment, and we would argue it is preferable in so far as the selection criteria are precisely defined and open to scrutiny. The specific criteria and logic are defined in the section below on Model Plausibility.

## ***Results and Discussion***

This assessment represents several improvements over the 2005 assessment. In particular, the dubious source/sink migration dynamics from the 7 area model have disappeared. Also, the updated CPUE series suggest that there is more consistency in abundance trends among areas, and this seems to be adequately described by the homogenous mixing characteristics assumed in the Multifan-CL model. The model predictions tend to fit (what we consider to be) the most reliable data reasonably well, describing declining CPUE trends, large seasonal migrations into and out of southern regions, and declining size composition in the inshore Australian fishery. However, none of the models are completely satisfactory. We use two example models to illustrate the variability in estimated dynamics that are supported by the same data.

This is followed by an outline of the logic and criteria used to distinguish between plausible and implausible models, and we attempt a synthesis of assessment results from the models thus identified as the plausible model ensemble.

### **Example Model Behaviour and Diagnostics**

We chose two model specifications to illustrate in detail (Table 5). Neither of these two models would be expected to represent the best fit to the data relative to the full set of models, because both have tighter constraints than some other model formulations. However, it would also be difficult to argue that we are confident enough in our assumptions and interpretation of the data that we should throw out one or both models as implausible on the basis of the quality of fit. The two models illustrate similar fits to the data, but rather different stock status implications. (e.g. On the basis of MSY-related reference points, Model 1 suggests that the stock is currently being severely over-exploited:  $F(2004)/FMSY = 2.5$ , while Model 2 suggests that the stock is not currently being over-exploited:  $F(2004)/FMSY = 0.27$ ). Other stock status reference points associated with these models (including the Hessian-Delta 95% confidence intervals for some quantities) are listed in Table 7. As described in the following section, Model 1 was rejected as implausible on the basis of prior perceptions of recruitment dynamics (not the fit to the data), while Model 2 was accepted in the plausible model ensemble.

Figure 15 illustrates that the Australian and New Zealand domestic CPUE predictions all fit the observations very well including recent declines and seasonality. The gross trends in the Japanese series fit reasonably well, except for the northern region (Area 1), which is poorly fit by all of the models explored. The contrast in the amplitude of the CPUE seasonal oscillations between the Australian and Japanese fleets operating in the same areas suggests that only part of this signal can be explained by migration.

Figure 16 illustrates that the two example models fit the general characteristics of the size sampling data reasonably well, but this is an aggregate over time, and obviously the fit is not as good in every year. Figure 17 illustrates the predicted and observed patterns in the size frequency data. The fishery for which we have the most data, and the strongest evidence of temporally changing size composition (fishery 6, Aus Area 2) is characterized very similarly in both models. They both capture the declining trend and seasonal cycles, but both models also seem to have a small bias (predictions undersized). Size trends in the other fisheries are not clear in predictions or observations (except possibly fishery 7, Aus Area 3), but long term means seem to correspond reasonably well, with large fluctuations in observations consistent with small sample sizes for most fisheries. Both example models seem to have small biases in the predictions of some fisheries, and these biases differ by model, but it is difficult to argue that one model is obviously better fit than the other overall.

Model inferences about the stock dynamics suggest much greater contrast than the fit to the data. The two stock recruitment curves have much different implications for stock productivity, but it would be difficult to argue that high steepness is more plausible than low steepness from a visual inspection of the estimated curves (Figure 19).

The models tend to prefer domed selectivity when the non-decreasing selectivity constraint is relaxed (Figure 18). This in turn seems to be a major factor determining the relative biomass in the different regions, early stock dynamics, and the ratio of spawning biomass relative to total biomass (Figure 20). Model 1 estimates a very large (dubious) initial spawning biomass (predominantly in Area 5) that declines continuously even during the early period of small catches. In contrast, the dome-shaped selectivity (Model 2) suggests that the proportion of spawning to total stock remains roughly constant over time, with Area 5 biomass lower than most other areas. Presumably the interactions among the alternative selectivity and mortality assumptions have the flexibility to support virtually any intermediate option between these two extremes and still fit the data as well as the example models.

Both models suggest non-stationary recruitment dynamics as inferred from Figure 21. In the absence of fishing, both models estimate that the stock would have been increasing from about 1950-1990. The early trajectories of the fished scenarios diverge however, with Model 1 decreasing continuously through the time series due to the effect of fishing, and model 2 increasing until 1990 despite the effect of fishing. These temporal trends in fished and unfished trajectories are not in themselves implausible, and we do note trends of a similar or greater magnitude estimated in other pelagic assessments (e.g. bigeye tuna assessment, Hampton et al 2005). However, we have also seen these trends estimated in a simulated stock with stationary production dynamics as a model artifact. The fact that the unfished biomass declines in both models coincident with the large increase in catches in the 1990s is suspicious. Figure 22 illustrates the impact of the fishery over time as a ratio of fished/unfished biomass from Figure 21, indicating that the fishery had a much greater effect in model 1 than model 2. This fishery impact pattern is qualitatively consistent with the expected effects of the catch history, which closely mimics the fishing mortality time series (Figure 23).

Figure 24 and Figure 25 provide a schematic illustration of the estimated migration patterns for the two example models. The patterns are similar in that they estimate large movement in and out of Areas 4 and 5, which show strong seasonality in CPUE trends. However, we would not have predicted large movements between Areas 1 and 4, and might have expected more movement in relation to spawning in Area 2. Without corroboration from tagging studies, it would be difficult to have much confidence in these estimates.

## **Defining Model Plausibility**

The process that we have used to reduce the total set of 500+ models to the “plausible ensemble” is described in the following 5 steps, in which we attempt to define and defend our selection criteria. Because of computational time constraints and the iterative nature of the model exploration, the following description is an abstraction of the much more circuitous process that actually occurred, but it is included as a useful record of how we reached the final product.

### **Step 1**

It was initially hoped that model combination A1 (Table 6) would provide a suitable coverage of the model uncertainty space. However, the models with the heavily down-weighted size sampling (s100) option resulted in unacceptably poor fits to the catch-at-size data, and seemed to be prone to numerical convergence problems.

## Step 2

Less extreme size down-weighting scenarios were defined in model combination B (Table 6). Examination of some of the reference point estimates from the s10 elements of combination A1 and A2 suggested that the relative area assumptions (AG, AJ, AS) and migration diffusion priors (DL, DH) probably had the smallest effect on the most sensitive reference points. Figure 26 and Figure 27 show the implications of the different assumptions on the TSB(2004)/TSB(MSY) reference point. In the interest of time, these two dimensions were dropped from subsequent grid evaluations.

## Step 3

The fully crossed elements of combinations A and B were merged to form the 144 model combination C. Inspection of these model results indicated that there were some problems with the models fits in several cases. We used two criteria to quantify the fit to the CPUE and size data. These criteria are closely related to objective function terms, but are easy to interpret and readily compared across models with different statistical assumptions. We describe the quality of fit to the CPUE series on the basis of the degree of agreement between predictions and observations (independent of the assumed variance in the assessment model) using the Root Mean-Squared Error, i.e. for fishery  $f$ :

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

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 the fit as opposed to random noise. While we are probably most interested in the systematic lack of fit, the two usually vary together (although this might not be true if the seasonality amplitude is poorly described). Figure 28 indicates the combination C quality of fit (RMSE) for the Australian Area 2 CPUE series. There is a degree of variability among models, but the RMSE suggests that ~75% of the models fit the core CPUE series at least as well as could be expected (corresponding to a CV generally less than 20% for the fisheries in which we have faith in the data. When averaged over all fisheries (not shown), the RMSE is much larger, but consistent with observed variability in the Japanese CPUE series and qualitatively similar in pattern to the fishery 6 results.

To compare the quality of fit between predicted and observed size frequency distributions, we use the effective sample size (McAllister and Ianelli 1997), which is independent of the assumed sample sizes in the assessment model objective function:

$$ESS_t = \frac{\sum_l p_{t,l}(1-p_{t,l})}{\sum_l (o_{t,l} - p_{t,l})^2}$$

where:

$p_{t,l}$  = proportion of predicted catch in length (or mass) bin  $l$

$o_{t,l}$  = proportion observed

and the ESS for fishery  $f$  is:

$$ESS_f = \frac{1}{N} \sum_t ESS_t .$$

Figure 29 illustrates the ESS index of fit for the inshore Australian fishery (with the best sample sizes). Not surprisingly, the quality of fit declines in relation to the sample size downweighting factor, although the difference between s5 and s10 was much smaller than between s10 and s20. An arbitrary minimum of Aus Area 2  $ESS > 150$  was adopted as a plausibility criterion. The poor size representation was also obvious in the southern area (SBT) fisheries (5 and 10). The failure to adequately capture the size composition in that region usually relates to an estimated selectivity that favours small fish (or is bimodal). This also tends to show up clearly as a size bias (Figure 30). We consider it reasonable to reject the models that show a large size bias in these southern fisheries. However, we might expect some degree of bias on the basis of the sex-aggregated nature of the growth curve (i.e. sampling in the New Zealand charter fishery indicates a preponderance of large female fish, in which case the compromise growth curve is probably predicting fish that are too small on average for these large individuals). On this basis, we removed models with a mean Area 5 size bias of  $> 20$  cm for the SBT fishery. We did not apply similar criteria to the Australian Area 5 fishery, because the size sampling is poor and the catch composition suggests a bit of a mix of northern and southern fishery characteristics.

#### Step 4

Combination D in Table 6 represents the 42 model subset of C that met the size bias and CPUE fit criteria (and to ensure valid convergence, we added a constraint of rejecting models with a maximum gradient  $> 10^{-2}$  of the objective function with respect to any parameter at the minimum). At this point all of the different assumptions from combination C were still represented in at least one of the models, except for the LS mortality assumption. Figure 31 illustrates that there is still considerable uncertainty in the reference points associated with this model subset. Key stock status estimates this subset of models are summarized in Table 7. The other criteria that we considered for assessing plausibility relate to model inferences that are not estimated directly. Figure 32 shows the maximum fishing mortality (for any individual age class) in area 5. Given that this is generally considered to be by-catch in the SBT fishery, we would not expect these fleets to deploy the most effective swordfish methods. The fact that some models estimate fishing mortalities higher than any other region and frequently greater than 1 (instantaneous annual F), suggests something implausible. This predominantly occurs in the models with non-decreasing selectivity. We hesitate to make the criteria too restrictive in this case, because a very high mortality of age 19+ fish might reflect an artefact of the interaction among mortality, selectivity and migration assumptions that has only minor relevance for the vast bulk of the stock. But we did decide to remove models with any age-specific  $F > 0.5$  (any area, any quarter). The final factor that we incorporated into the plausibility criteria relates to the stock recruitment relationship. There is rarely enough data to estimate a stock recruitment relationship (and frequently evidence for recruitment regime shifts). On the basis of the high fecundity of large females, and evidence for apparently rapid rebuilding in other oceans (e.g. North Atlantic, Ortiz 2005) we would probably expect higher steepness (more recruitment compensation) than the steepness 0.4 scenario, and restricted the final model combination to models that included steepness of 0.65 – 0.9.

## Step 5

Combination E consists of the 10 model subset from C that meets all the data fitting criteria, maximum F limits for area 5, and the minimum steepness prior). We refer to this as the most plausible model ensemble. The extremes from the model diagnostics from model set C and E are compared along with the two example models in Table 8. Figure 33 illustrates that even within this restricted subset of models, there remains considerable uncertainty represented in the TSB(2004)/TSB(MSY) reference point. It appears that the interactions among assumptions are also important. The sr1 and SF options tend to be more optimistic than models with the sr4 and SM combinations, such that there seems to be limited overlap across the two combinations (i.e. no SM sr1 model combinations made the final selection). Figure 34 illustrates the estimated SSB trajectories for each of the 10 models in the plausible ensemble.

## Stock Status Synthesis

We have little confidence in MSY-related estimates because they are inevitably sensitive to the stock recruitment relationship, which is usually poorly determined. MSY can also be a misleading concept of dubious usefulness when production dynamics are non-stationary. In the swordfish case, we also do not have a lot of confidence in the SSB estimates. While this is a key quantity for management considerations (e.g. to quantify the risk of recruitment overfishing), we are not confident that the models can reliably quantify SSB for several reasons: mature females represent a small proportion of the total catch, they are caught in the highest proportions in the southern part of the range which is poorly sampled by the fisheries, and the sex-specific growth, mortality and migration characteristics are aggregated in the current models.

We have more confidence in ratios of relative abundance at two points in time, because these reference points are less sensitive to stock recruitment assumptions and absolute abundance scaling problems. Furthermore, in this system, we have more confidence in the last 10 years because this corresponds to the period of the best data (except that the last couple years tend to be more uncertain than earlier years because of the partially recruited year classes).

In the following summary, and Table 7, we report against reference points with an ad hoc definition of uncertainty bounds based on the outcome of the plausible model ensemble. We report the median and the range of the MPD estimates from the plausible models. This will probably result in a practical interpretation similar to a Bayesian posterior or frequentist confidence interval. However, it is important to emphasize that each MPD result is based on an individual model fitting. If the model at one of the bounds happened to constitute a perfect unbiased estimator for the quantity of interest, then there would actually be a 50% probability that the true value was outside of the stated uncertainty bounds. This approach to uncertainty quantification has less of a theoretical basis than the usual approach, but we think that it will usually lead to a more reasonable estimate of the real uncertainty in systems where model uncertainty seems to exceed statistical uncertainty conditional on a



particular model. The following stock status conclusions are presented roughly in order of perceived reliability:

- 1) We consider the relative Total Stock Biomass (TSB) 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. The MPD results from the plausible model ensemble indicate:
  - $TSB(2004)/TSB(1995)$  median 0.70, range (0.56 – 0.74).
- 2) All of the Spawning Stock Biomass (SSB – roughly corresponding to age 10+ fish) reference points are more uncertain than TSB because SSB represents a small portion of the catch, and may be badly biased by natural mortality assumptions, and the model aggregation of sex-specific characteristics of growth, mortality and migration. Furthermore, the southern range of the stock seems to consist predominantly of mature females, but this region is poorly sampled by the fishery and it is difficult to relate abundance in this southern part of the population to the core population.
  - $SSB(2004)/SSB(1995) = 0.75$  (0.51 – 0.86).
- 3) 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 produce).
  - $TSB(2004) / TSBNF(2004) = 0.59$  (0.31 – 0.69)
  - $SSB(2004) / SSBNF(2004) = 0.49$  (0.15 – 0.65).
- 4) 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 seriously 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 probably above levels that would sustain MSY and fishing mortality is probably below  $F(MSY)$ .
  - $TSB(2004)/TSB(MSY) = 1.7$  (0.87 – 3.0)
  - $SSB(2004)/SSB(MSY) = 3.4$  (0.75 – 6.4)
  - $F(2004)/F(MSY) = 0.70$  (0.33 – 2.2).
- 5) The apparent optimism of the MSY-related reference points is countered by the stock projections, which suggest biomass declines over the short term (assuming deterministic future recruitment according to the estimated stock recruitment relationships, and sustained effort at 2004 levels):
  - $TSB(2009) / TSB(2004) = 0.88$  (0.78 – 1.00)
  - $SSB(2009) / SSB(2004) = 0.84$  (0.71 – 0.86)

Key stock status results are summarized graphically in Figure 35 and Figure 36. Figure 35 illustrates the joint uncertainty in biomass and fishing mortality relative to

MSY levels. This plot also illustrates how the model uncertainty greatly exceeds the parameter uncertainty estimated conditional on a specific model being correct (for the example models). It is also interesting to note that even though the subjective plausibility criteria reduced the number of candidate models to <10% of the original number, the total uncertainty space was not extremely restricted as a result. Figure 36 illustrates the relationship between estimates of recent biomass decline, and projected biomass at 2004 effort levels.

## Assessment Issues for Future Consideration

This assessment process has improved our understanding of the swordfish fishery, and helped to identify and quantify the effects of a number of uncertainties. Additional analyses to the input data and reformulation of the assessment models might improve our understanding of some issues. But for many issues, additional data would need to be collected, and some uncertainties dependent on the oldest data will probably never be satisfactorily resolved. In particular, we consider the following:

- The spatial structure of the assessment models might not be appropriate. While it has been useful to think of the SW Pacific subunits conceptually, it is doubtful that the assessment model can reliably quantify the movement dynamics without direct observations (i.e. conventional and/or electronic tagging). If there is substantial interannual variability in migration patterns and fishing characteristics, the spatial structure might not be particularly effective in defining homogenous units. It is also unclear the degree to which seasonal changes to CPUE reflect fish movements or changing catchability. Furthermore, the projection results do not suggest large changes in relative abundance among sub-areas over the short term. So it is not obvious that the spatial structure provides any real advantage over an aggregated assessment in this case. However, it is also not obvious that the assumed spatial structure should lead to worse inferences than an aggregated model either. Brief exploration of a single area Multifan-CL model using an aggregate relative abundance index (calculated in consideration of issues related to the relative effective areas and catchabilities of the component fleets), did not result in a satisfactory model, but this might be revisited in more detail. In either case, the effects of stock structure and migration in relation to the broader Pacific might undermine the operational assumption of the SW Pacific as a closed system.
- The current definition of area 5 is not ideal. It was intended to partition the southern (SBT-targeted) fisheries from the more northern fisheries which have different catch size (and sex) characteristics. However, this was not achieved, as the fleet-specific size compositions in area 5 could only be explained with differential selectivity, rather than different availability. Explaining the size disparity through differential migration would have been more in keeping with the spirit of the assessment, but it is also not clear that the model has sufficient flexibility in age-dependent migration to reproduce the observed size partition. The Area 5 fishery potentially has important implications for spawning biomass calculations, and detailed exploration of the problems in linking relative abundance across these northern and southern regions might be fruitful.

- It would be very useful to acquire a better understanding of the DWF fleets in the equatorial SW and South-Central Pacific. The recent increasing catch rate trends in these areas might be an encouraging sign of good recent recruitment, in which case the assessment as presented is probably a bit pessimistic because of the heavy downweighting of the tropical portion of the stock (but this would also suggest that the migration link between the equatorial and core SW Pacific populations might not be strong). We have opted for the more conservative interpretation, such that the increasing CPUE of the Japanese fleet is interpreted as likely due to changes in targeting practice. This might also explain the increasing trend estimated during the 1960-80s in the Japanese fleet, as there was a move from yellowfin to bigeye targeting. We look to our colleagues in the distant water fishing nations for insight into these issues. Detailed consideration of the spatial extent of all the fleets in the sub-areas would be useful for revisiting the relative abundance assumptions among areas.
- There is strong evidence for sex-specific growth and migration characteristics in swordfish (natural mortality divergence would also seem likely). Wang et al (2005) illustrate through swordfish assessment simulations that model biases can be reduced by including sex-dimorphism. However, it is not clear whether benefits will be realized given the other sources of assessment uncertainty and paucity of sex-specific data for this stock. It would be sensible to include sex sampling along with size sampling as part of routine fisheries data collection.
- Very little is known about natural mortality of swordfish, other than inferences based on the oldest observed individuals. Concerted tagging studies, and direct age estimation from routine hard parts sampling (by sex) might help to reduce these uncertainties somewhat.
- We consider research priorities for inputs to the assessment (roughly in order) to be:
  1. Reliable relative abundance indices. Application of standard survey techniques using commercial gear would be very useful for understanding changing catchability, as would detailed documentation of changing gear deployment and targeting practices. The relationship between oceanographic variability and fish distributions will also help in this respect. The relationship between abundance in fished and unfished areas may have a major influence on the assessment.
  2. Improved sampling of fish size (using standard units) and sex by area, would be very useful, as would collection of hard parts for age estimation.
  3. Electronic tagging (archival and satellite) would be useful for understanding migration characteristics within the SW Pacific and in relation to adjacent basins, plus helpful in the quantification of habitat preferences, which might improve interpretation of catch rate variability.

4. Conventional tagging can provide useful estimates of natural and fishing mortality, and migration.
5. Genetic studies might be useful in further refining our understanding of stock structure, or examining close kin relationships for the quantification of spawning biomass. Genetic tags from *in situ* biopsy sampling might be preferable to conventional tagging for this species.
6. Total catches are generally assumed to be known very well in these models. Understanding of discarding and depredation would help to validate this assumption.

The unfortunate fact that stock assessments cannot make precise 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 Management Strategy Evaluation. Campbell and Dowling (2003) describe a possible approach for how this might work for the ETBF swordfish fishery. We see the most useful role of these integrative models to be the quantification of uncertainty for use in the development of Management Procedures that are robust to the underlying uncertainties to the extent possible. The Australian Department of Agriculture, Fisheries and Forestry has recently initiated a program to have domestic harvest strategies in place for all commonwealth managed target species. 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.

## ***Acknowledgements***

Thanks to David Fournier, and the Multifan-CL development team for providing the software. John Hampton, Pierre Kleiber, and Adam Langley provided useful suggestions to the assessment and critical insight required to navigate undocumented features in the software. We are indebted to the countless people that have collected the fisheries data over the years, and especially grateful to Naozumi Miyabe, Talbot Murray, Lynda Griggs, Roberto Sarralde Vizuet, and Tim Lawson for providing much of the data. Funding support was provided by the Australian Fisheries Management Authority.

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**Table 1. SW Pacific swordfish assessment fishery definitions.**

Fishery Number	Area	Fishing Nation(s)
1	1	Japan (plus other DWF and PIN)
2	2	Japan (plus other DWF and PIN)
3	3	Japan (plus other DWF and PIN)
4	4	Japan (plus other DWF and PIN)
5	5	Japan (plus other DWF and PIN)
6	2	Aus
7	3	Aus
8	5	Aus
9	4	NZ Domestic
10	5	NZ Charter

**Table 2. Relative catchability among fleets for each of the SW Pacific areas (mean CPUE 1998-2004 for the indicated fleet) divided by (mean CPUE 1998-2004 for the most reliable CPUE series in the same area). e.g. On the basis of the standardized catch rates, the Australian fleet appears to be more than 3 times as efficient as the Japanese fleet in areas 2-3, but less than twice as efficient in Area 5.**

Area \ Nation	Australia	Japan	New Zealand
1	n/a	1	n/a
2	1	0.31	n/a
3	1	0.21	n/a
4	n/a	0.28	1
5	1	0.57	0.3

**Table 3. Effective relative areas assumed for regions 1-5 in the SW Pacific swordfish assessment. “AG” (Geographic) assumes that the fishery catchability applies equally to the whole area (uniform density within an area). “AJ” (Japanese), assumes that the catchability applies to the maximum number of 1x1 degree squares fished within each area (from any individual year), i.e. the fished region defines the extent of the stock. “AS” (Swordfish) assumes that the spatial distribution of the stock within an area corresponds to the maximum number of 1x1 degree squares fished within each area in which at least one swordfish was actually caught.**

Area	Relative Area Assumption		
	AG	AJ	AS
1	0.468	0.428	0.417
2	0.078	0.158	0.207
3	0.078	0.113	0.151
4	0.123	0.093	0.116
5	0.247	0.208	0.109

**Table 4. Assumptions examined in the model uncertainty Exploration. The Abbreviations correspond to labels in Figure 26-Figure 33.**

	Value	Abbreviation
Stock recruitment steepness	0.4	h4
	0.65	h65
	0.9	h9
Recruitment deviations	0.1	sr1
	0.4	sr4
M (mean) See fig Figure 13 for age-specific M	0.16	L
	0.28	H
	0.24	LS
	0.41	HS
Selectivity Constraint	Unconstrained	SF
	Non-decreasing	SM
Catch-at-Length/Mass Downweighting factor	5	s5
	10	s10
	20	s20
	100	s100
Effective Area	Geographical	AG
	Max. Japanese Effort	AJ
	Max. Swordfish caught	AS
Diffusion Priors Mode	Low (0.1)	DL
	High (1.0)	DH



Table 5. Example Model Assumptions. Abbreviations defined in Table 4.

<b>Example Model</b>		
<b>Assumption</b>	<b>1</b>	<b>2</b>
Stock Recruitment Curve Steepness	h9	h4
Recruitment Deviation from SR CV	sr1	sr4
Natural Mortality	L	L
Fishery Selectivity	SF	SM
Size Sample down-weighting	s10	s10
Migration Diffusion Priors	DL	DL
CPUE effective Area	AG	AG

**Table 6. Model Uncertainty Parameter Grid. Model Combinations A, B and C represent all possible combinations of the listed assumptions. Combinations D and E represents the subset of Cross C that meets the indicated plausibility criteria. Assumption abbreviations are defined in Table 4. In D and E, the indicated assumptions are represented in at least one model, but not in every possible combination.**

	<b>Model Combination</b>					
	<b>A1</b>	<b>A2</b>	<b>B</b>	<b>C</b>	<b>D</b>	<b>E</b>
<b>Plausibility Criteria*</b>					<b>1-4</b>	<b>1-6</b>
<b>Assumption</b>						
Stock Recruitment Curve Steepness	h4, h65, h9	h65, h9	h4, h65, h9	h4, h65, h9	h4, h65, h9	h65, h9
Recruitment Deviation from SR CV	sr1, sr4	sr1, sr4	sr1, sr4	sr1, sr4	sr1, sr4	sr1, sr4
Natural Mortality	L, LS, H, HS	L, LS, H	L, LS, H, HS	L, LS, H, HS	L, H, HS	L, H
Fishery Selectivity	SM, SF	SM, SF	SM, SF	SM, SF	SM, SF	SM, SF
Size Sample down-weighting	s10, s100	s10	s5, s20	s5, s10, s20	s5, s10, s20	s5, s10
Migration Diffusion Priors	DL, DH	DL	DL	DL	DL	DL
CPUE effective Area	AG, AJ	AG, AJ, AS	AG	AG	AG	AG
<b>Total number of models</b>	<b>384</b>	<b>72</b>	<b>96</b>	<b>144</b>	<b>42</b>	<b>10</b>

**\*Model Plausibility Criteria:**

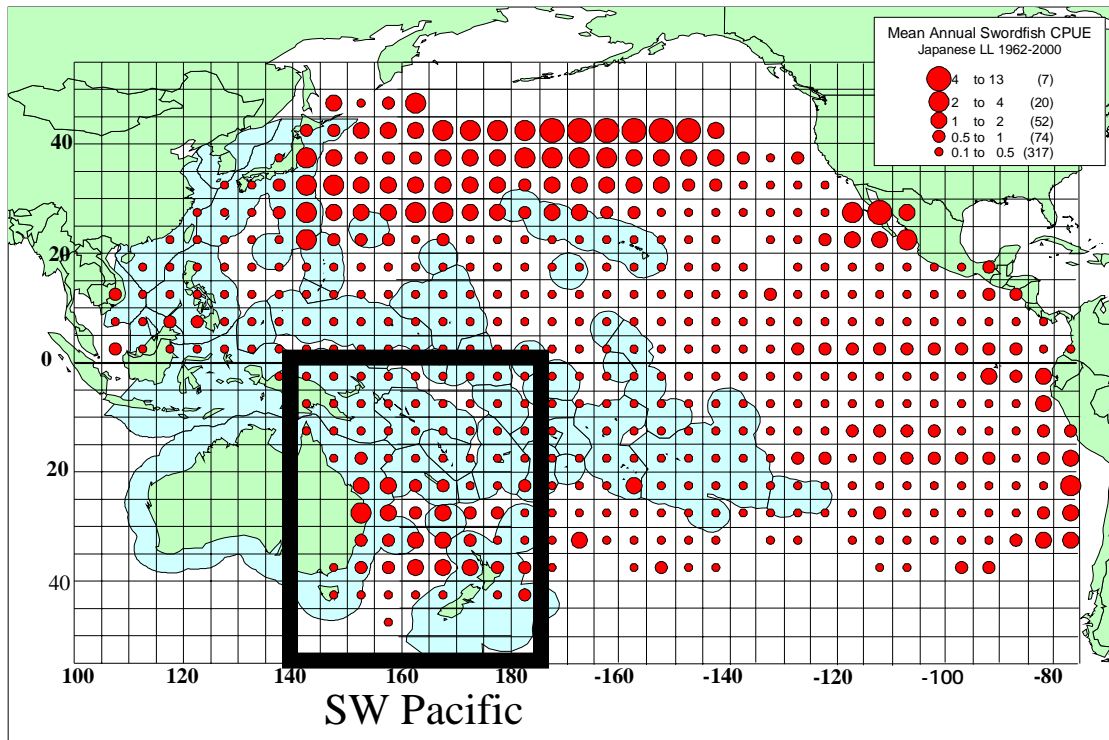
- 1) adequate numerical convergence: maximum gradient  $< 10^{-2}$
- 2) adequate fit to core CPUE series: Fishery 6,7,9 CPUE RMSE  $< 0.2$
- 3) adequate fit to southern area size composition: Fishery 5,10 Abs(mean size bias)  $< 20\text{cm}$
- 4) adequate fit to core fishery size data: Fishery 6 ESS  $> 150$
- 5) southern fishing mortality sensible: max. F(Area 5, any age, any quarter)  $< 0.5$
- 6) moderate – high recruitment compensation:  $h \geq 0.65$

**Table 7. Stock Status Reference Point Summary.** MPD uncertainty bounds represent the median and range from the 10 models in the plausible ensemble. Example model confidence limits are estimated using the inverse Hessian-Delta method. TSB = Total Stock Biomass, SSB = Spawning Stock Biomass, NF designates the quantity that would have occurred if there had been no fishing, F indicates fishing mortality as the Catch(mass)/TSB, A23 indicates area 2 and 3 combined (all other values refer to the whole SW Pacific region)

Management Quantity	MPD Lower Bound	MPD Median	MPD Upper Bound	Example Model 1 MPD (95 % C.I.)	Example Model 2 MPD (95% C.I.)
<b>Model Combination D</b> (plausibility defined by numerical convergence, and fit to CPUE and Size data)					
TSB(2004)/TSB(1995)	0.55	0.703	0.904		
SSB(2004)/SSB(1995)	0.422	0.586	0.862		
2004 TSB/TSB(NF)	0.267	0.649	0.892	n/a	n/a
2004 SSB/SSB(NF)	0.072	0.374	0.715	n/a	n/a
TSB(2004)/TSB(MSY)	0.367	1.56	3.42	0.81 (0.72-0.91)	2.97 (2.5-4.1)
SSB(2004)/SSB(MSY)	0.194	1.99	7.1	0.72 (0.60-0.85)	7.48 (6.3-8.8)
TSB(2009)/TSB(2004)	0.612	0.859	1.03		
TSB(2009)/TSB(2004) A23	0.445	0.817	1.01		
SSB(2009)/SSB(2004)	0.666	0.803	0.953		
F(2004)	0.0277	0.065	0.191		
F(2004) /F(MSY)	0.18	0.975	3.9	2.80 (2.5-3.1)	0.33 (0.26-0.39)
<b>Model Combination E</b> (plausibility defined by Combination D, but also includes constraints on maximum F and minimum stock recruitment curve steepness)					
TSB(2004)/TSB(1995)	0.563	0.696	0.74		
SSB(2004)/SSB(1995)	0.509	0.753	0.862		
2004 TSB/TSB(q=0)	0.312	0.586	0.694		
2004 SSB/SSB(q=0)	0.148	0.487	0.654		
TSB(2004)/TSB(MSY)	0.873	1.72	2.97		
SSB(2004)/SSB(MSY)	0.749	3.35	6.43		
TSB(2009)/TSB(2004)	0.782	0.876	0.998		
TSB(2009)/TSB(2004) A23	0.749	0.843	0.982		
SSB(2009)/SSB(2004)	0.714	0.802	0.861		
F(2004)	0.0319	0.0569	0.159		
F(2004) /F(MSY)	0.326	0.7	2.24		

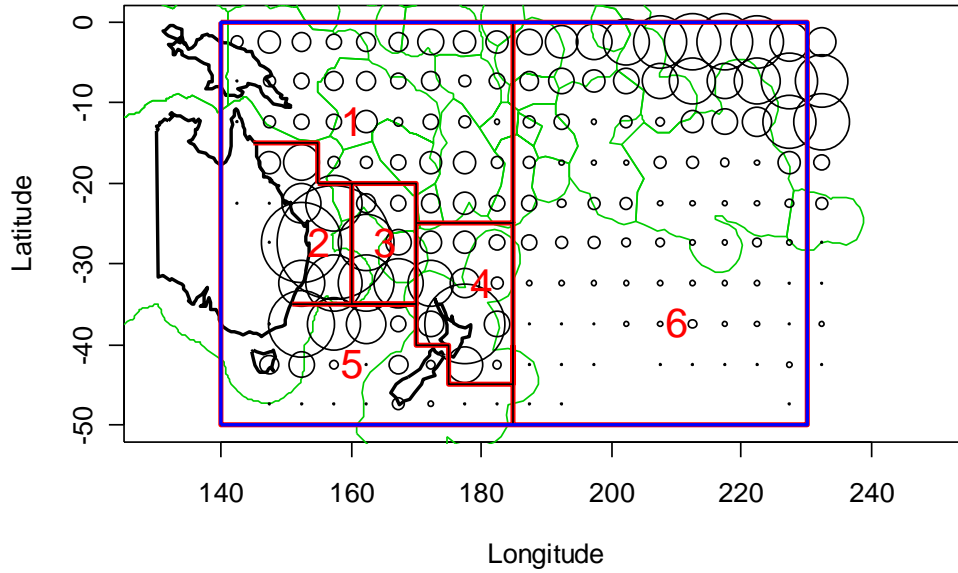
**Table 8. Quality of fit characteristics from MPD estimates of example models and extremes from model combinations (E corresponds to the 10 model plausible ensemble). The highlighted diagnostics were explicitly used in the model selection criteria.**

Goodness of fit criteria	Model Combination				Example model 1	Example model2
	C min	C max	E min	E max		
maximum F	9.08E-05	12400	0.136	0.442	0.244	0.139
maximum F A4	0.000125	2.22	0.22	0.401	0.305	0.224
<b>maximum F A5</b>	<b>0.000191</b>	<b>9.72</b>	<b>0.203</b>	<b>0.489</b>	<b>0.181</b>	<b>0.489</b>
size Bias Aus A2	-7.72	-1.26	-4.51	-2.34	-3.96	-4.51
size Bias Aus A5	-39.2	25.8	-26.4	12.4	25.8	-24.8
<b>size Bias NZ A5</b>	<b>-70</b>	<b>7.46</b>	<b>-4.43</b>	<b>6.08</b>	<b>6.04</b>	<b>-3.75</b>
ESS f1	6.78	23.8	14.1	22.8	16.5	14.3
ESS f2	23.7	72	36.8	59.8	58.6	37.1
ESS f3	8.58	15	11.8	15	14.4	11.9
ESS f4	26.8	54.1	38.7	52.6	51	39.3
ESS f5	2.46	33.2	14.9	33.2	32.2	15.2
<b>ESS Aus A2</b>	<b>52.6</b>	<b>238</b>	<b>184</b>	<b>238</b>	<b>214</b>	<b>184</b>
ESS Aus A3	42.2	189	111	143	123	114
ESS Aus A5	4.44	9.92	6.24	8.67	6.29	6.24
ESS NZ A4	16.3	46.2	27.4	41.7	34.2	29.1
ESS NZ A5	2.24	15	8.24	15	14.8	8.34
ESS all f	29.3	69.7	52.2	69.7	64.2	52.5
cpueRMSE f=1	0.505	0.849	0.522	0.661	0.505	0.661
cpueRMSE f=2	0.512	1.21	0.516	0.589	0.548	0.529
cpueRMSE f=3	0.757	1.01	0.834	0.92	0.822	0.834
cpueRMSE f=4	0.644	0.816	0.647	0.717	0.707	0.672
cpueRMSE f=5	0.899	1.79	0.988	1.14	1.01	1
<b>cpueRMSE f=6</b>	<b>0.102</b>	<b>2.75</b>	<b>0.12</b>	<b>0.184</b>	<b>0.123</b>	<b>0.138</b>
<b>cpueRMSE f=7</b>	<b>0.085</b>	<b>0.194</b>	<b>0.105</b>	<b>0.138</b>	<b>0.109</b>	<b>0.124</b>
cpueRMSE f=8	0.453	4.27	0.453	0.548	0.617	0.459
<b>cpueRMSE f=9</b>	<b>0.136</b>	<b>0.228</b>	<b>0.142</b>	<b>0.156</b>	<b>0.147</b>	<b>0.143</b>
cpueRMSE f=10	0.824	1.09	0.881	0.975	0.889	0.93
cpueRMSE all	0.675	1.1	0.685	0.735	0.686	0.7



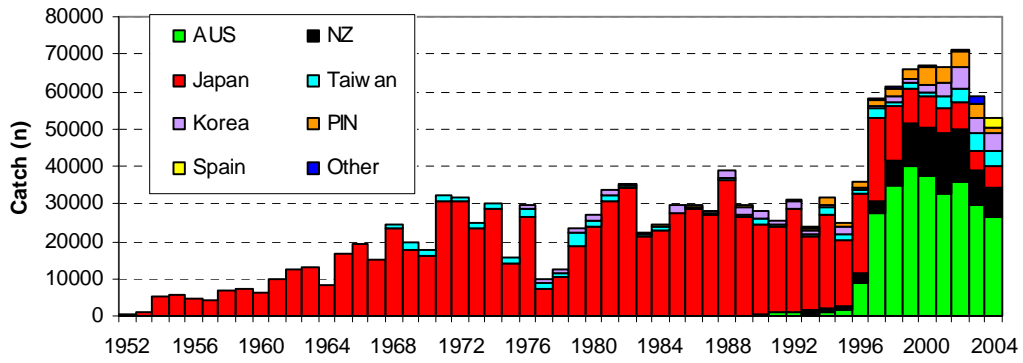
**Figure 1.** Rectangle outlines the operational definition of the South-West Pacific swordfish stock for assessment purposes. The red circles indicate mean CPUE observed in the Japanese longline fishery 1962-2000.

**All nation Swordfish total Catch in Numbers  
1952-2004**



**Figure 2. Spatial considerations in the development of the SW Pacific swordfish assessment. Regions 1-5 correspond to the core assessment area, where we have the best understanding of the fisheries data and biology. Area 6 was initially defined for sensitivity trials but this was not pursued for reasons described in the text. The area of the black circles represents the relative catch in each 5x5 degree square summed over 1952-2004.**

South-West Pacific AREAS 1 - 5



South-Central Pacific - AREA 6

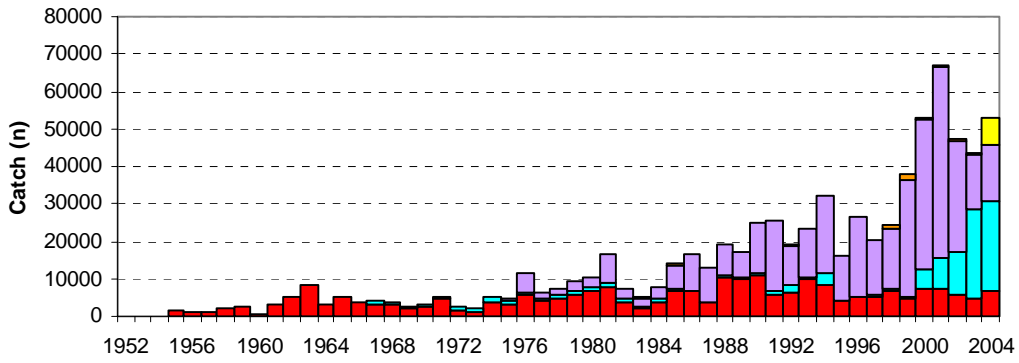


Figure 3. Total swordfish catch history in the southern WCPO convention area, South-West (areas 1-5) and South-Central (area 6) are defined in Figure 2.

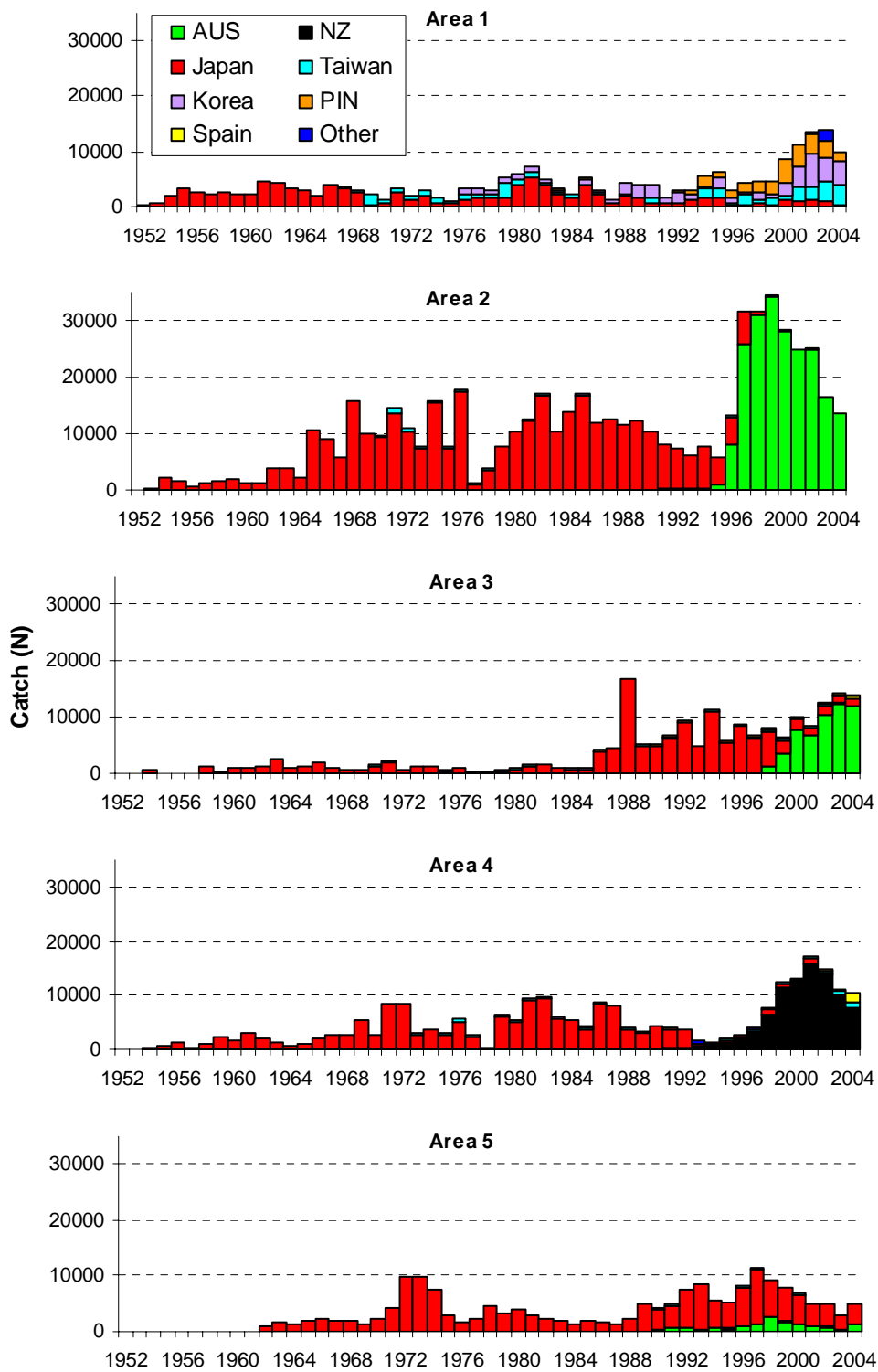
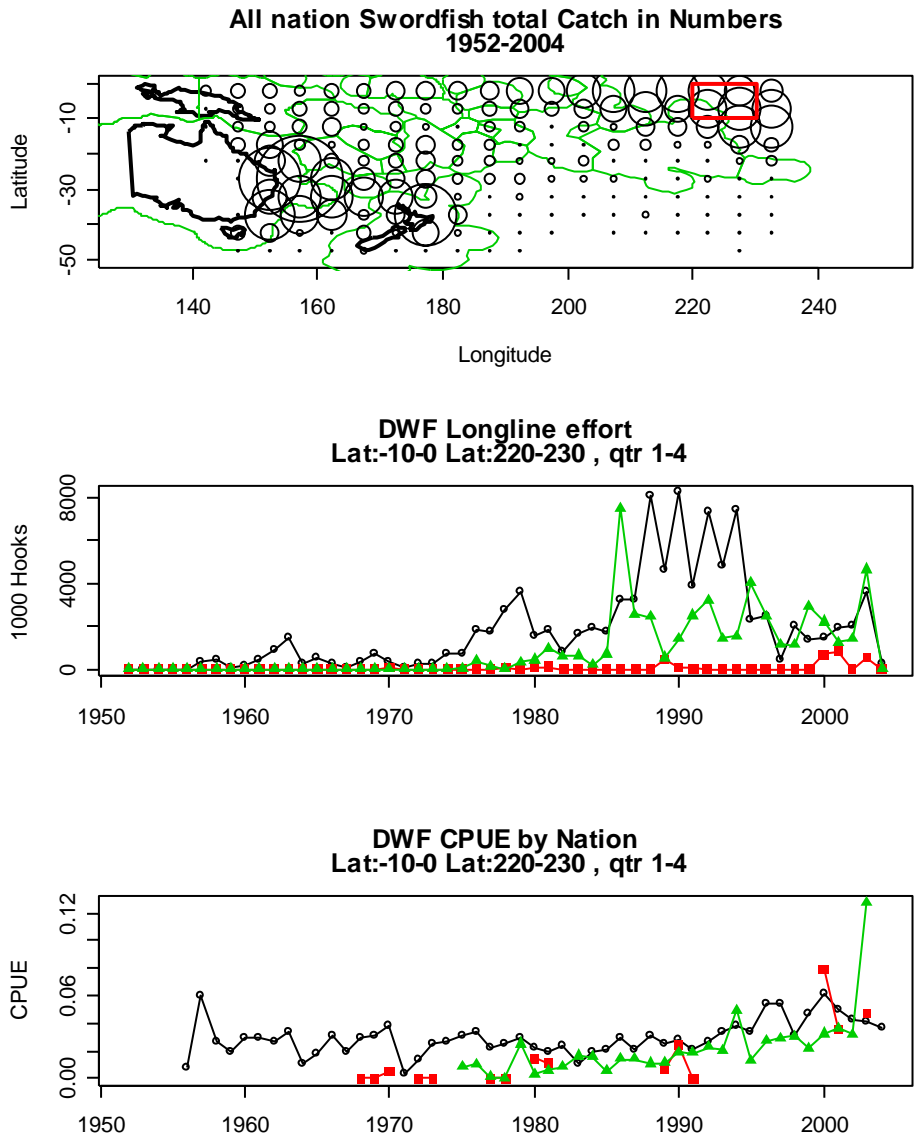
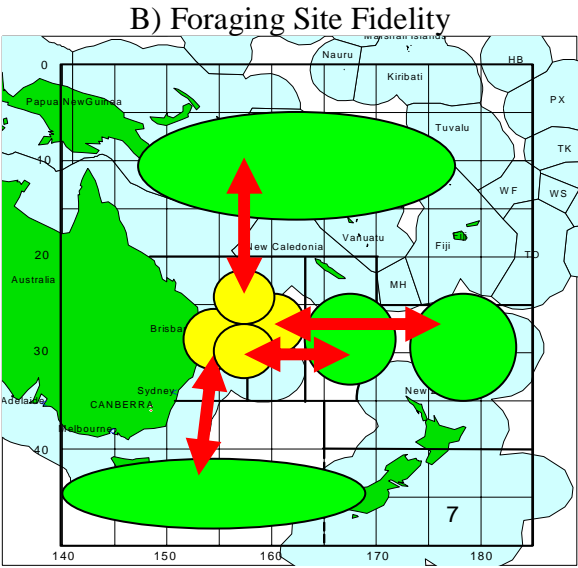
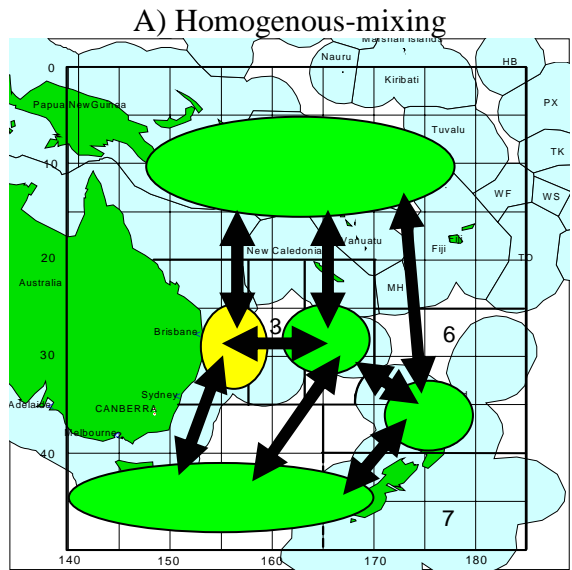


Figure 4. SW Pacific swordfish catch by area (corresponding to Figure 2) and fishing nation.

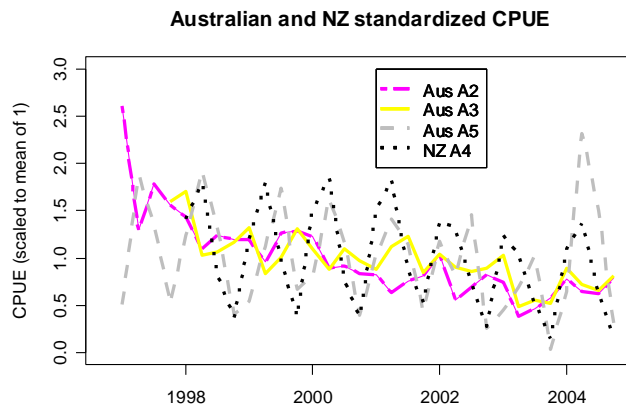


**Figure 5. Temporal trends in nominal CPUE series for the outlined equatorial region in the top panel map. Japanese fleet in black (circles), Taiwanese in red (squares) and Korean in green (triangles).**

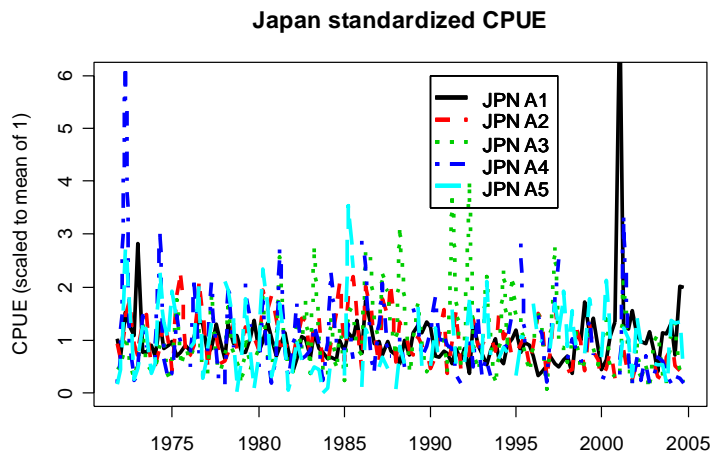




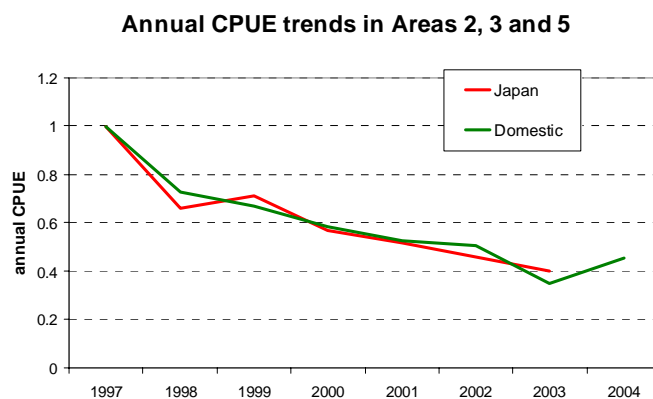
**Figure 6. Schematic representation of the different migration models discussed. Arrows indicate possible movement links, ovals indicate sub-populations (green indicates foraging grounds; yellow indicates spawning grounds). In panel B, it is assumed that the sub-populations mix for spawning purposes, but mature individuals always return to the same foraging areas.**



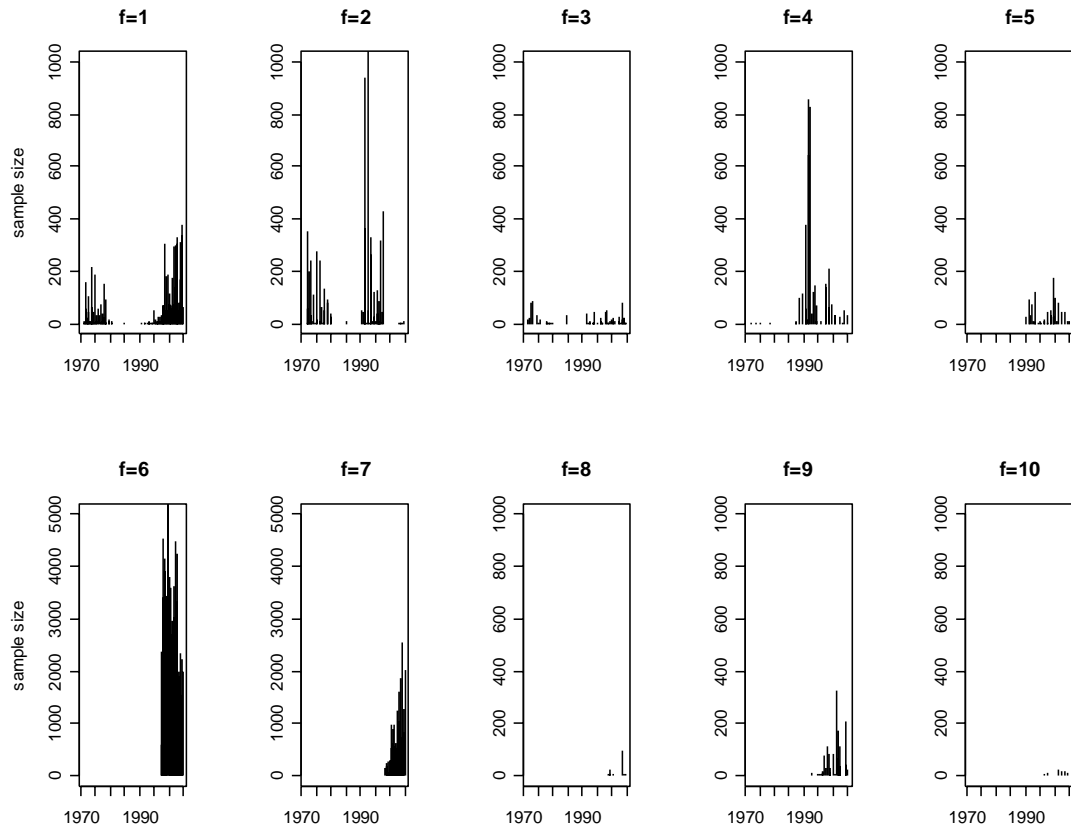
**Figure 7. Standardized Catch rates (normalized to a mean of unity) for the Australian and New Zealand domestic fleets over the time period that we assume CPUE provides a useful relative abundance index.**



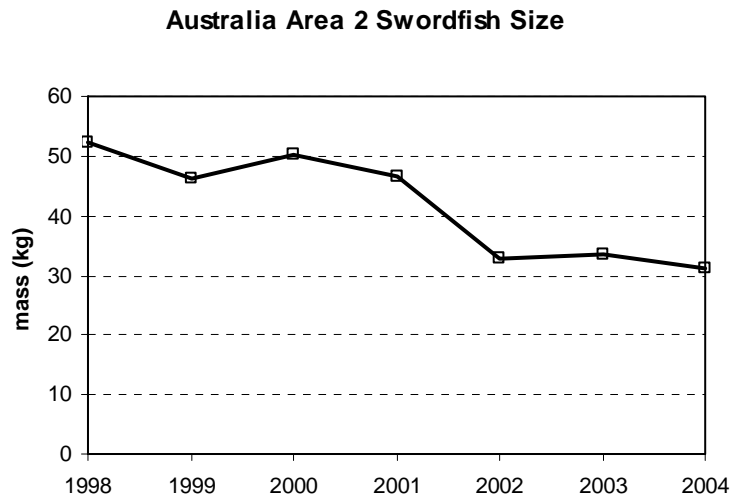
**Figure 8. Standardized catch rates (normalized to a mean of unity) for the Japanese fleet over the time period considered to be informative for the assessment.**



**Figure 9. Comparison of Japanese and Australian CPUE trends in the areas of overlap in the SW Pacific. Both series are re-scaled relative to 1997 for comparison.**



**Figure 10. Quarterly swordfish size frequency sampling by fishery. Note the Y-axis scale differs for Australian fisheries 6 and 7 relative to the others.**



**Figure 11. Declining mean annual swordfish sizes observed in the heavily sampled Australian Area 2 fishery.**

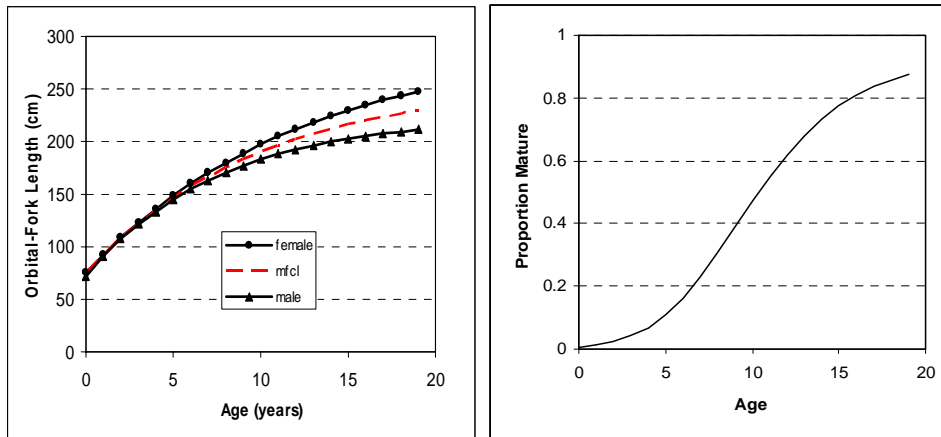


Figure 12. Growth and maturity of SW Pacific swordfish. Left panel indicates the mean age-length relationships for males and females estimated in (Young and Drake 2004), plus the mean of the two used in the sex-aggregated model (mfcl). Right panel is the estimated maturity for females (Young and Drake 2002), adopted for the whole population in the assessment.

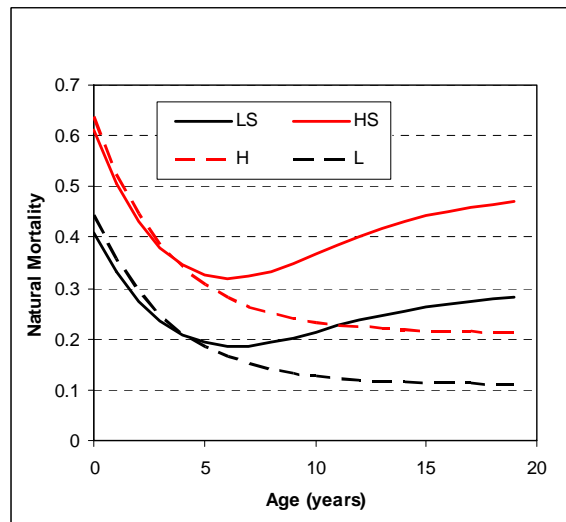


Figure 13. Alternative swordfish natural mortality vectors (instantaneous, annual units) assumed in the model uncertainty grid.

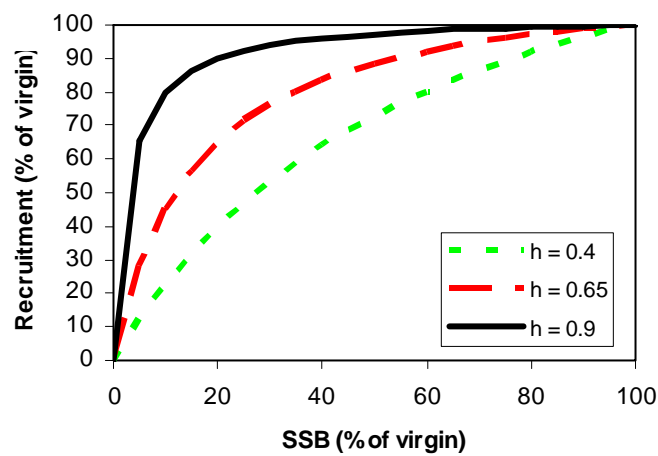


Figure 14. Three levels of stock recruitment curve steepness ( $h$ ) assumed in the model uncertainty grid.

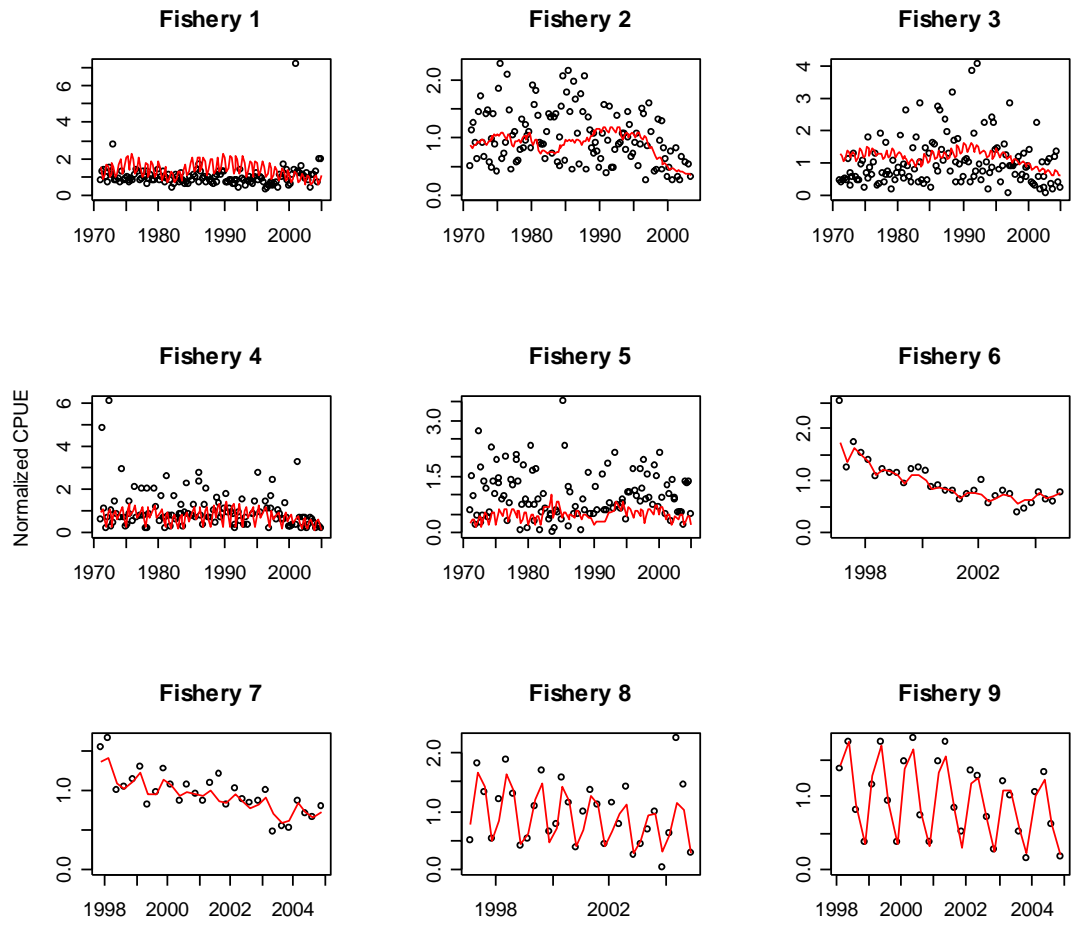
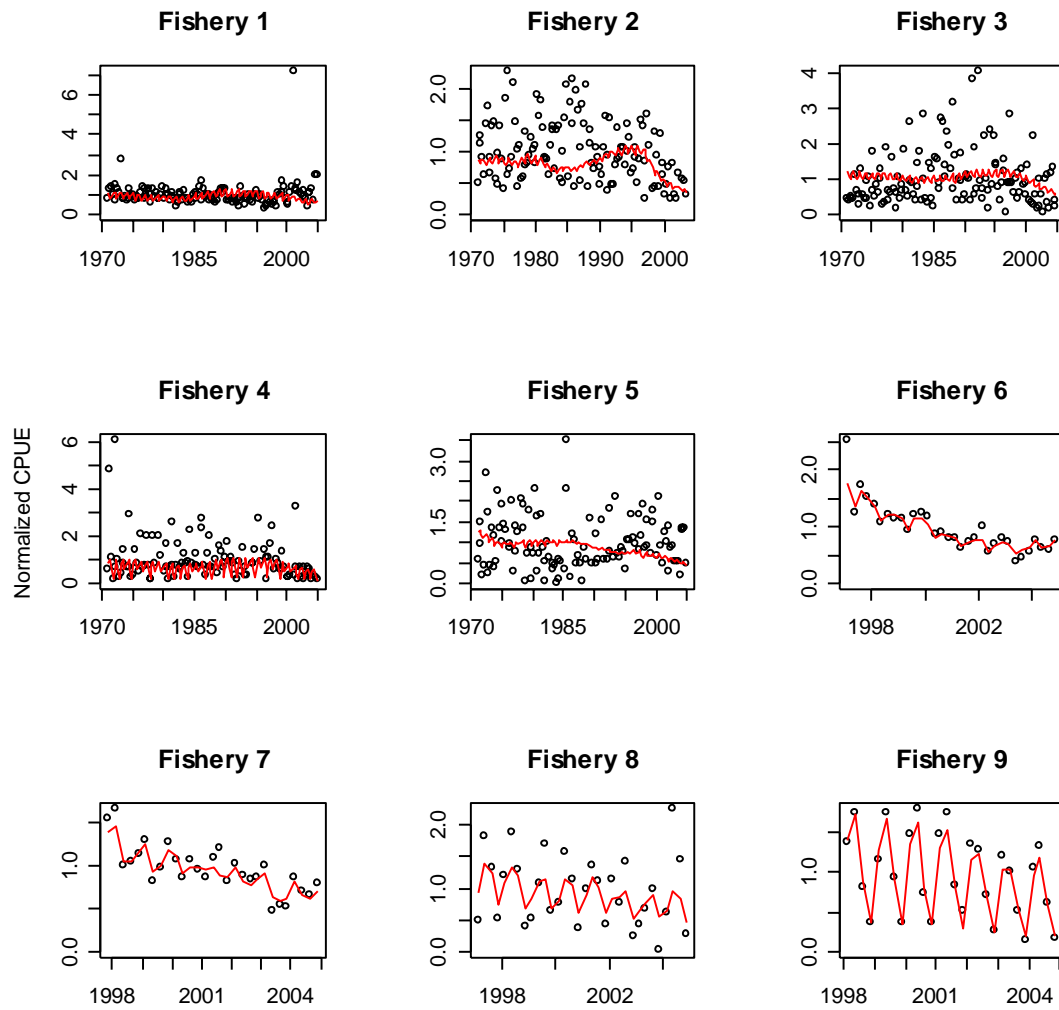
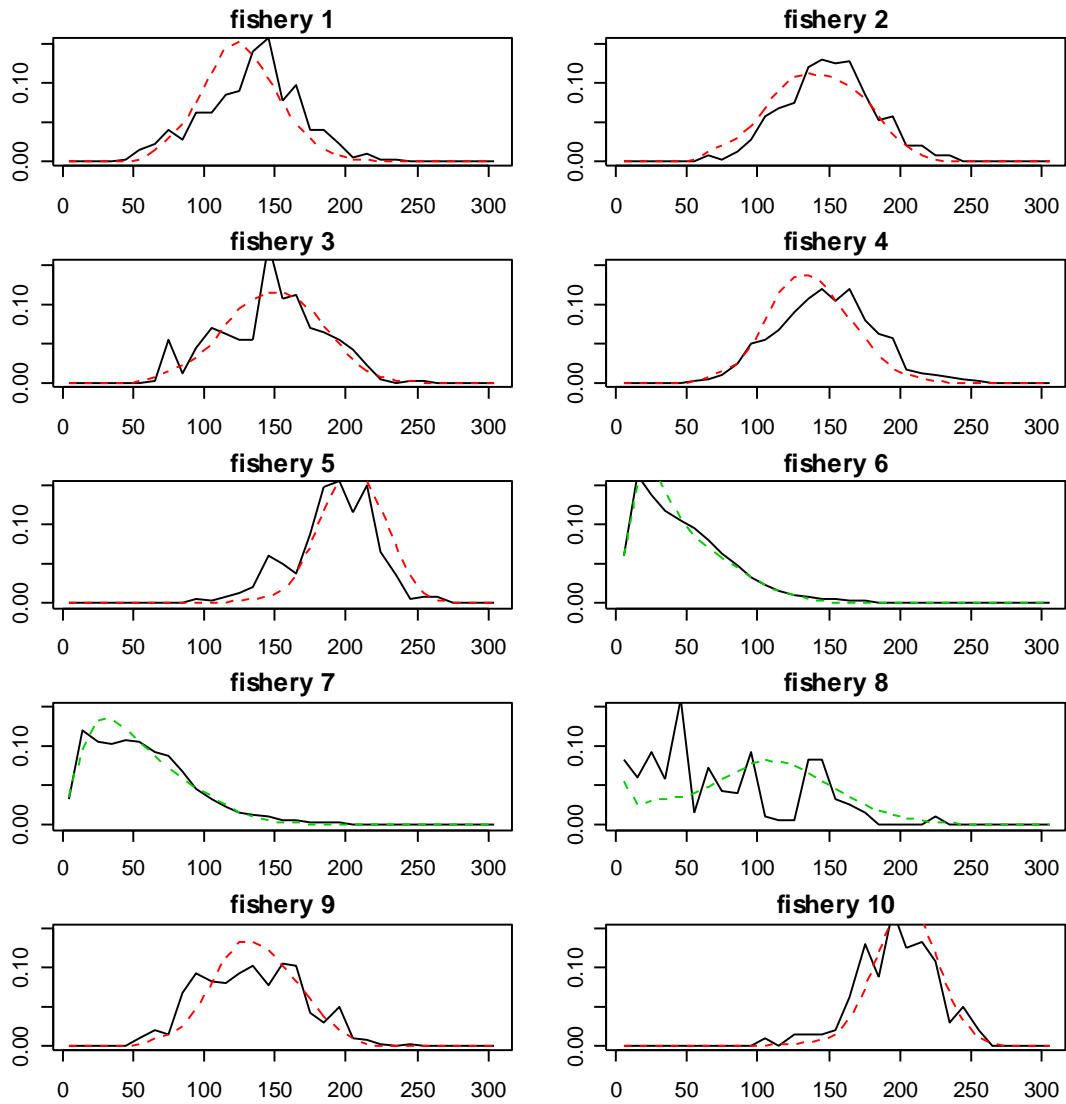


Figure 15 B. Predicted (line) and observed (circles) CPUE from the MPD fit of example model 1. Note that the models also estimate small deviations between predicted and observed total catches, and these deviations are not represented in these plots.



**Figure 15 B. Predicted (line) and observed (circles) CPUE from the MPD fit of example model 2.**



**Figure 16A. Predicted (broken lines) and observed (solid lines) swordfish catch size composition (summed over time) estimated from the MPD results for example model 1. Note that fisheries 6-8 (green) are trunked mass (kg), while the others are POF length (cm).**

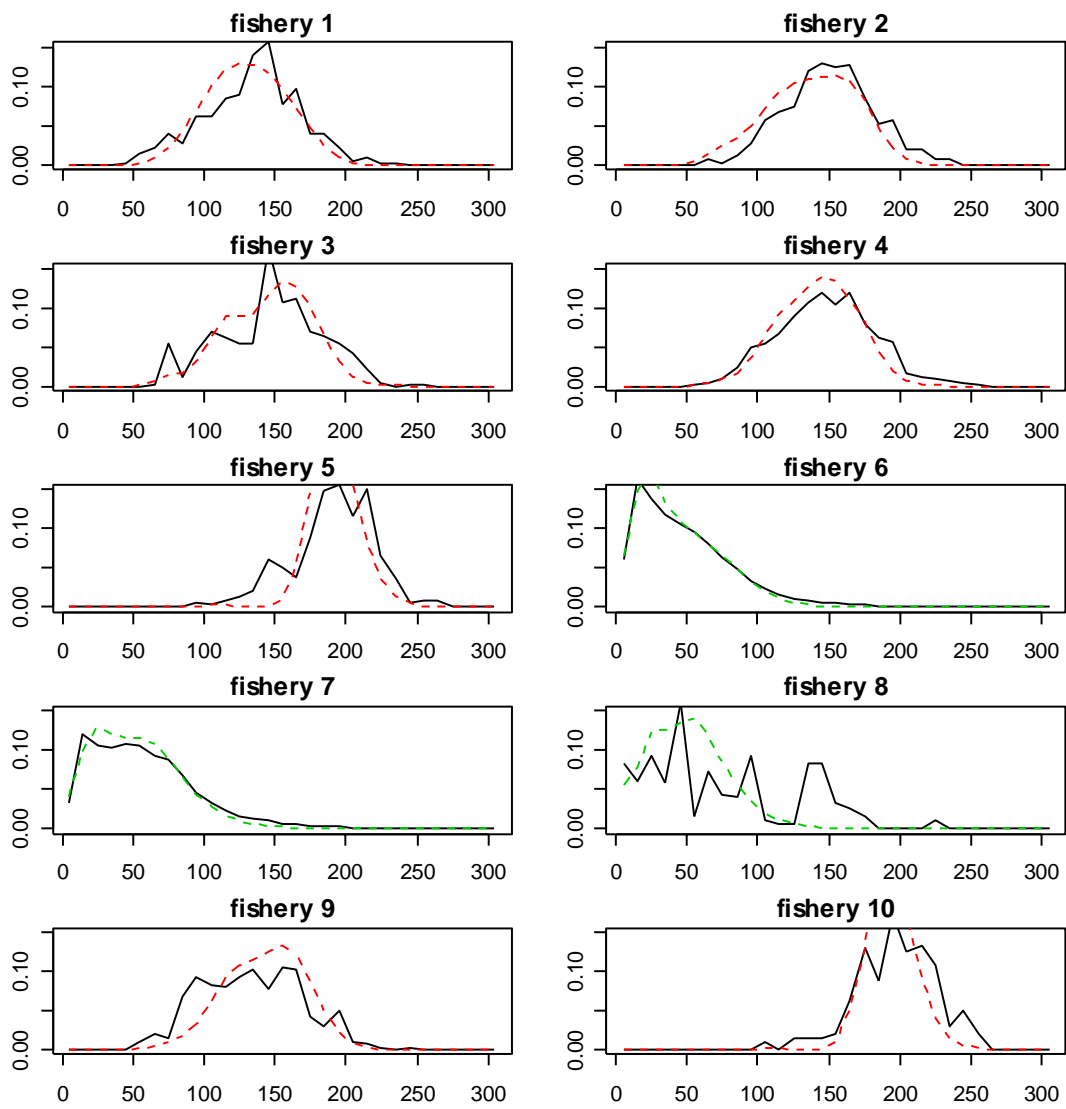


Figure 16B. Predicted (broken lines) and observed (solid lines) swordfish catch size composition (summed over time) estimated from the MPD results for example model 2. Note that fisheries 6-8 (green) are trunked mass (kg), while the others are POF length (cm).



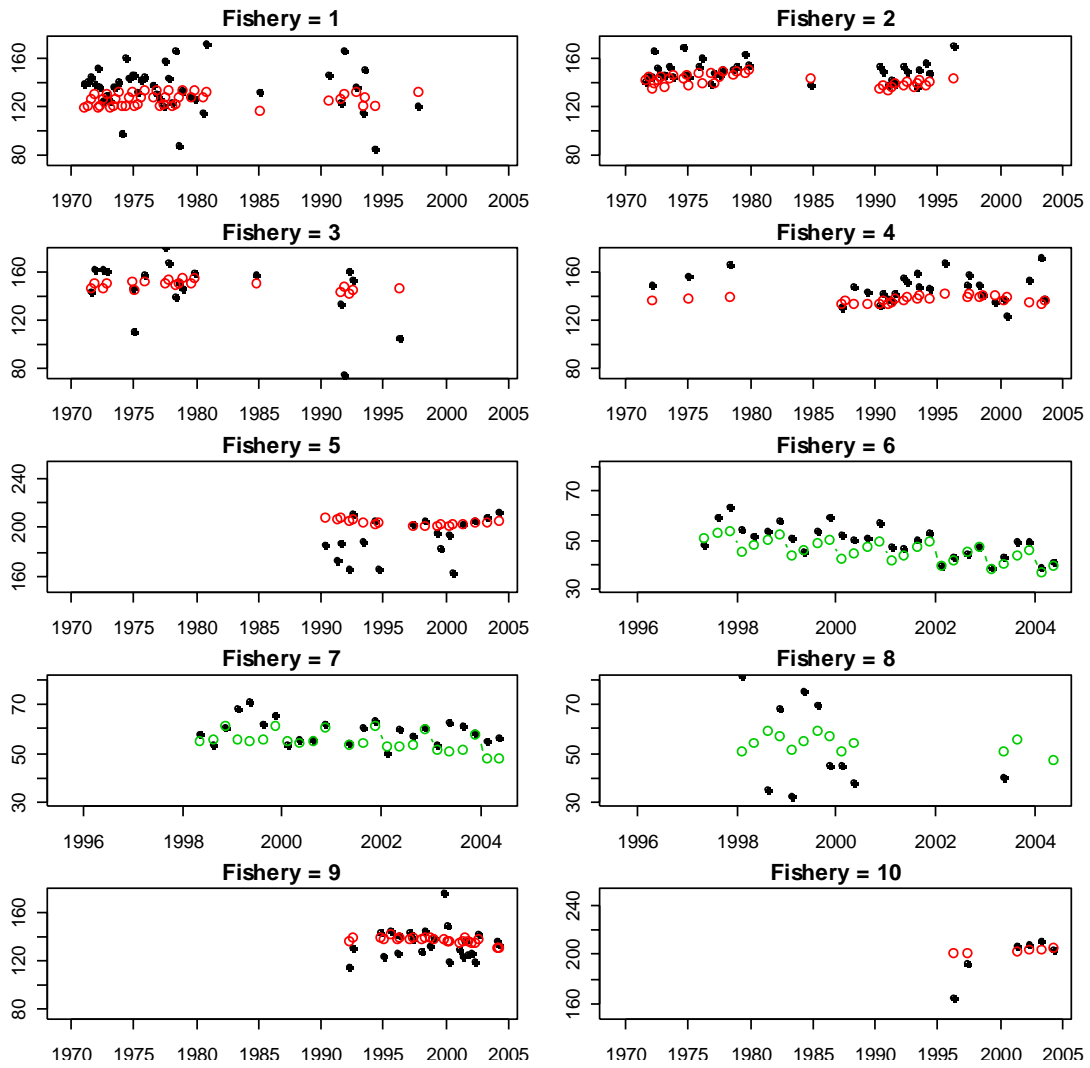


Figure 17A. Example model 1 predicted (hollow) and observed (solid) mean sizes for example model 1. Note axes differ in scale and units (trunked mass for fisheries 6-8, post-orbital fork length for all others).

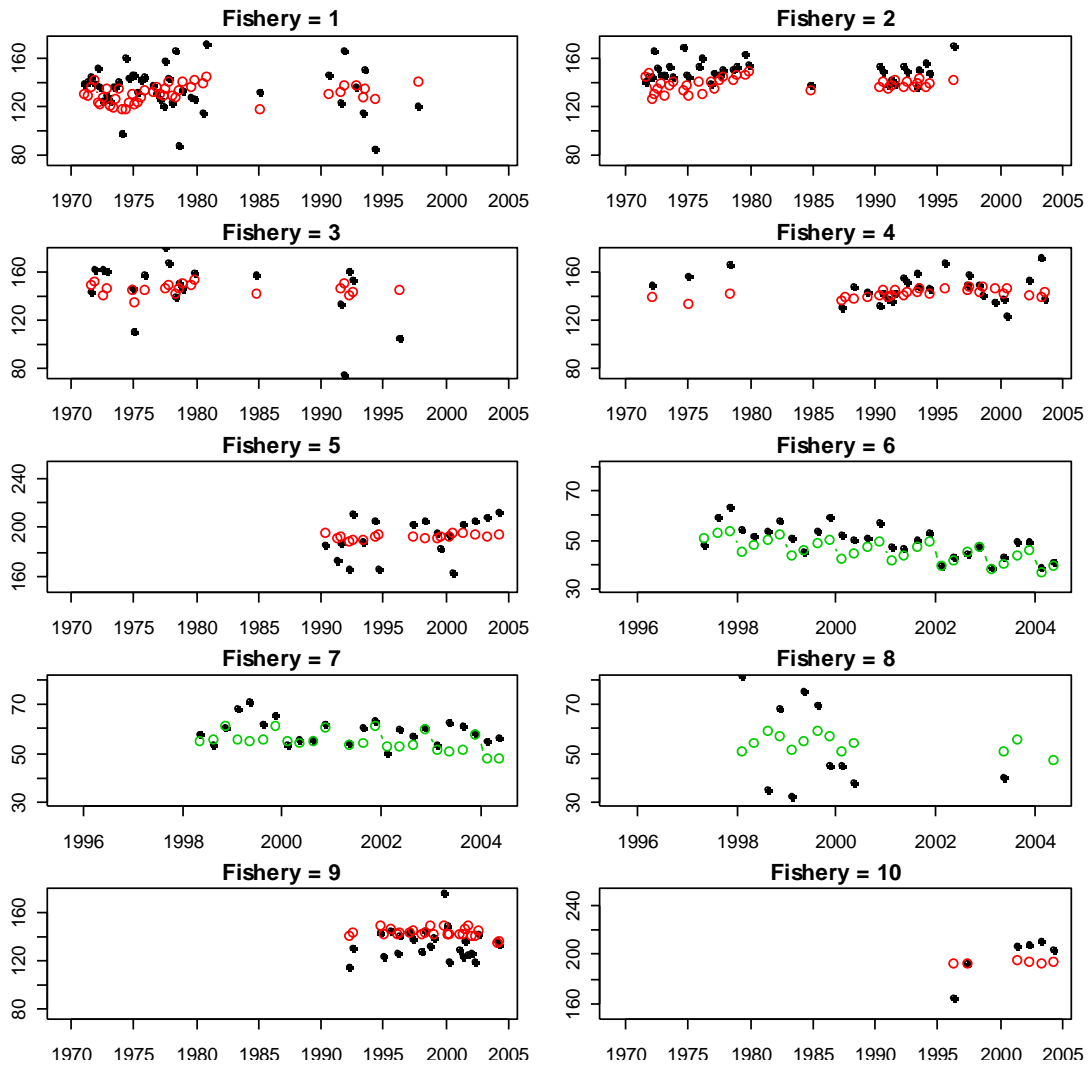


Figure 17B. Predicted (hollow) and observed (solid) mean sizes for example model 2.

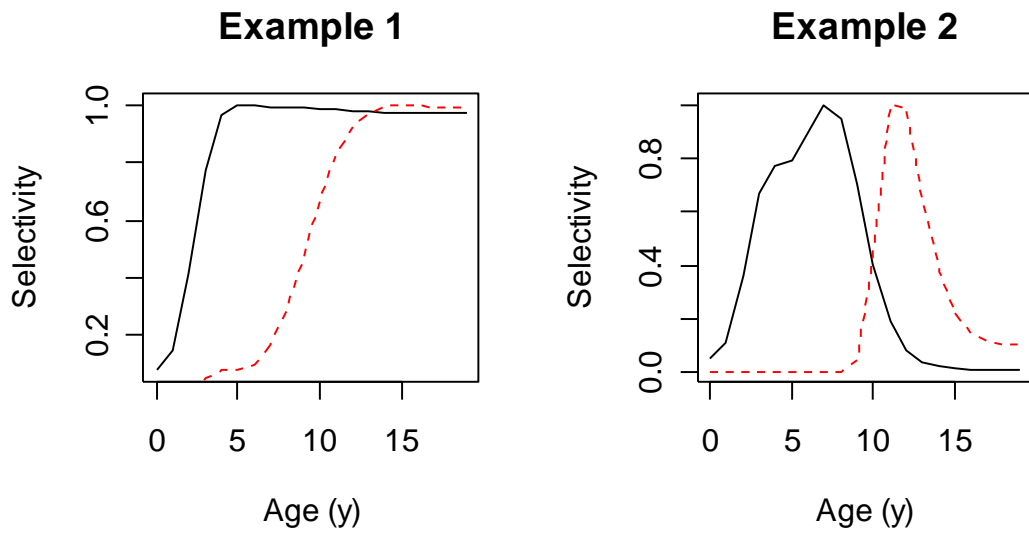


Figure 18. MPD fishery selectivity for example model 2 (right panel) and 1 (left panel). Black (solid) line corresponds to fisheries 1-4 and 6-9; red (broken) line corresponds to fisheries 5 and 10.

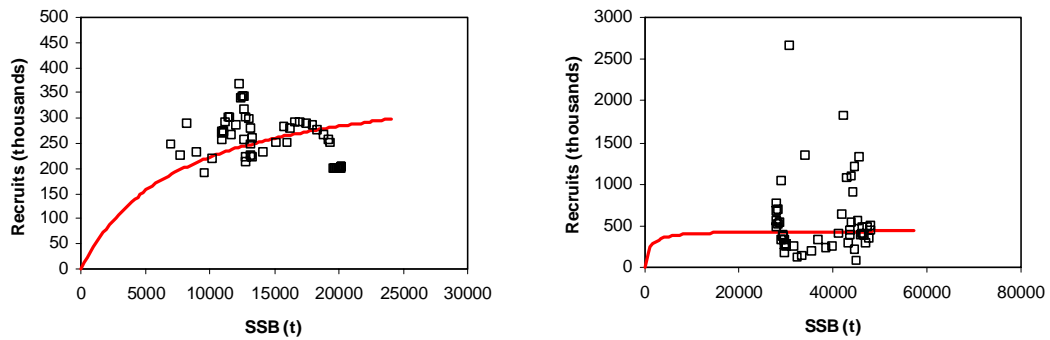


Figure 19. Stock recruitment curves and estimated recruitment deviations corresponding to example models 1 (left) and 2 (right). Note that the steepness levels were fixed in the assessment.

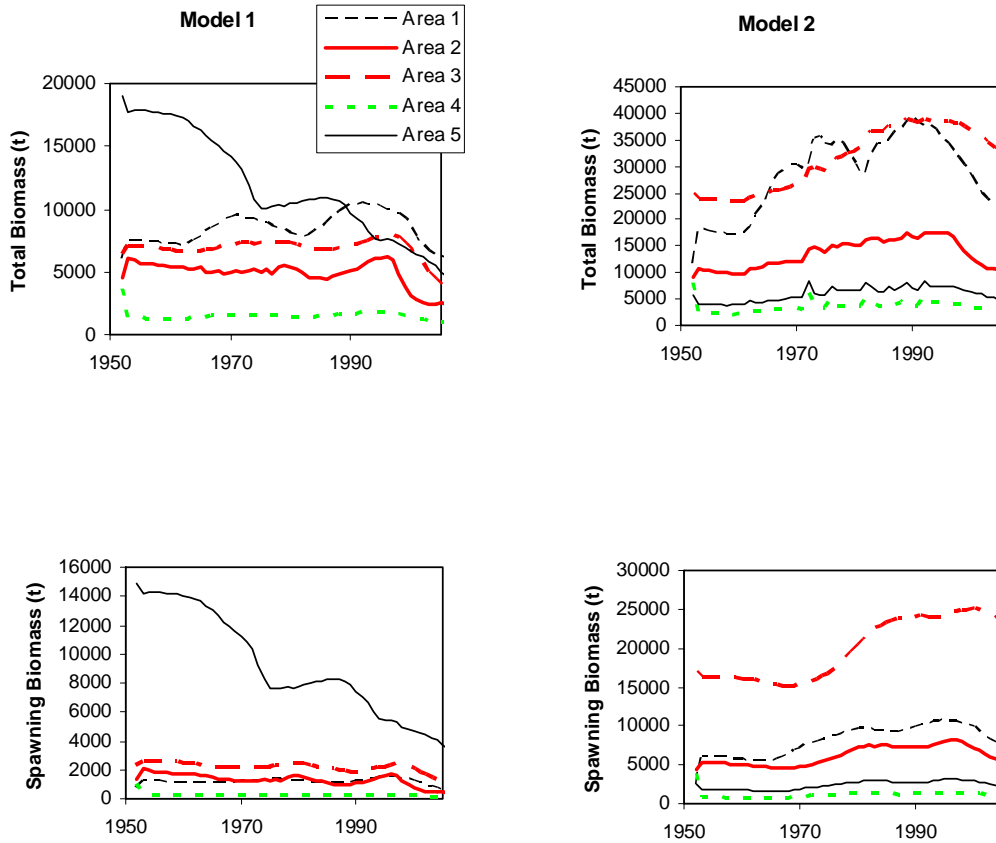


Figure 20. MPD estimates of total (top panels) and spawning (bottom panels) biomass by region for the two example models (left = 1, right = 2). Note that seasonal patterns are not included.

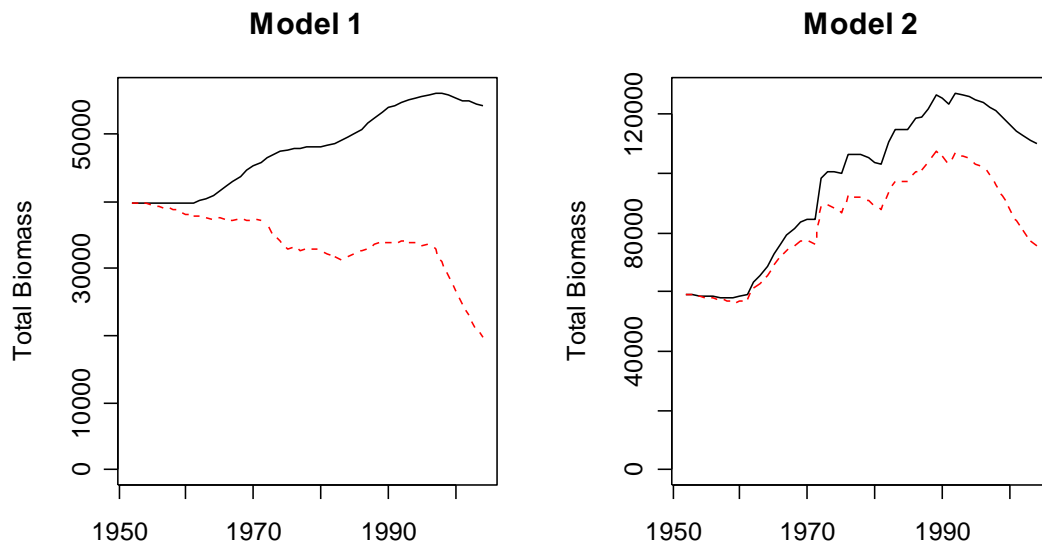


Figure 21. MPD estimates of unfished (black solid line) and fished (red broken line) total Biomass for the two example models.

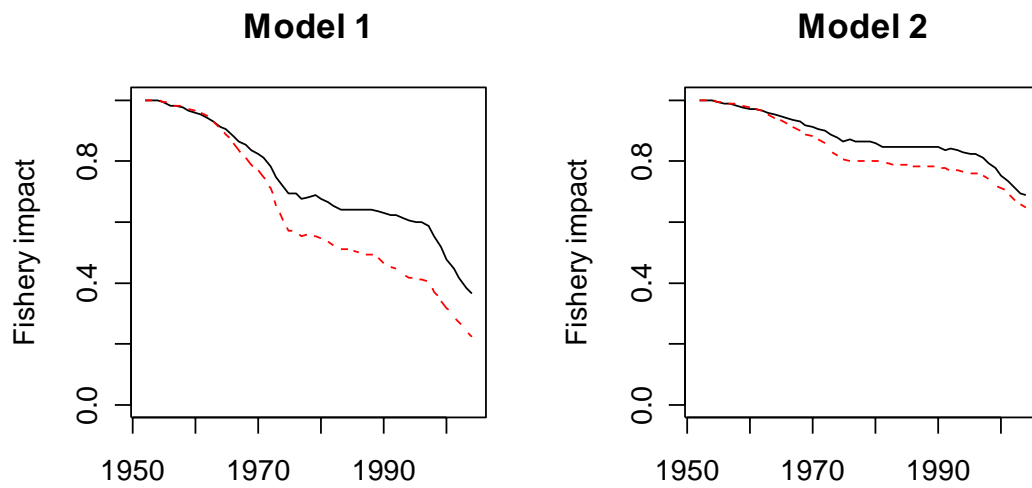


Figure 22. Estimated fishing impact on the stock from the two example models. Solid black lines indicate the ratio of  $TSB(\text{fished})/TSB(\text{unfished})$ ; broken red lines indicate  $SSB(\text{fished})/SSB(\text{unfished})$ .

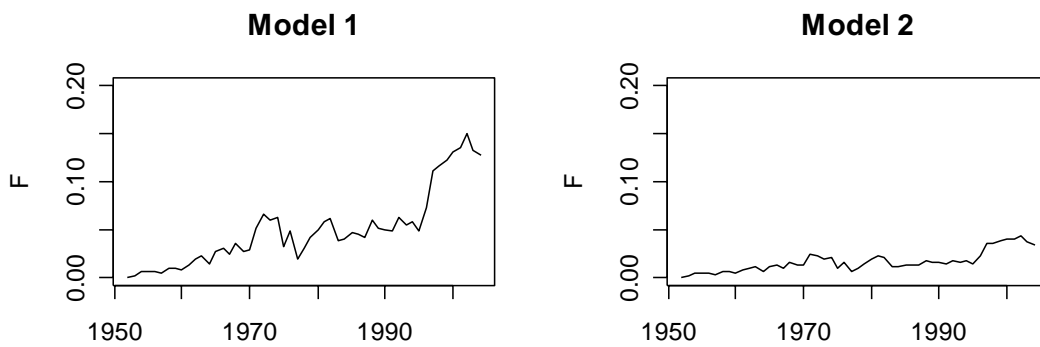
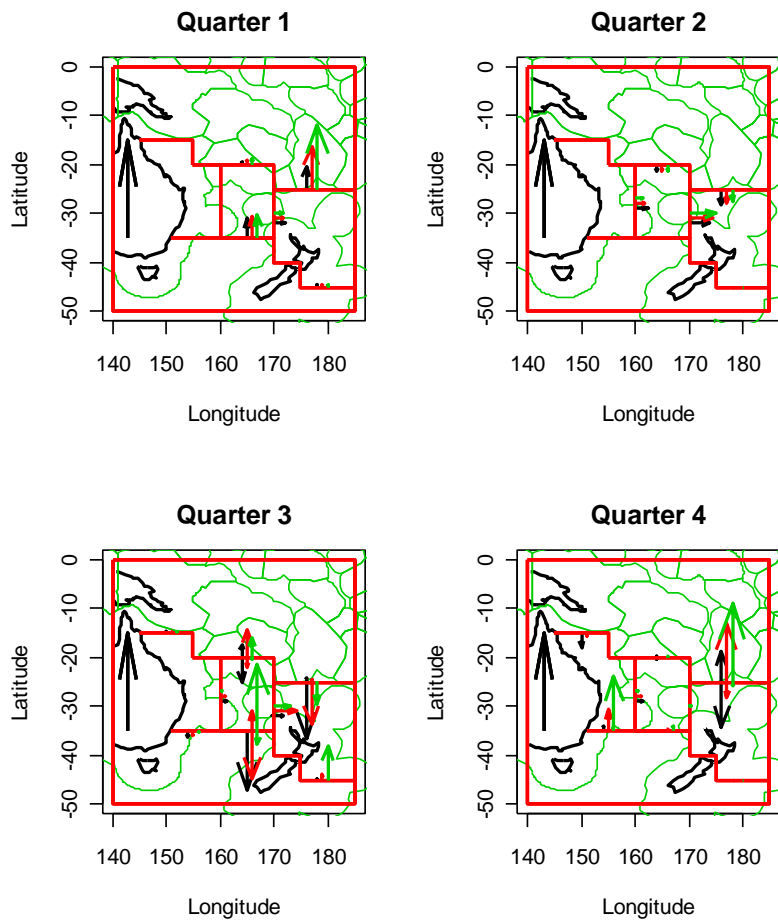
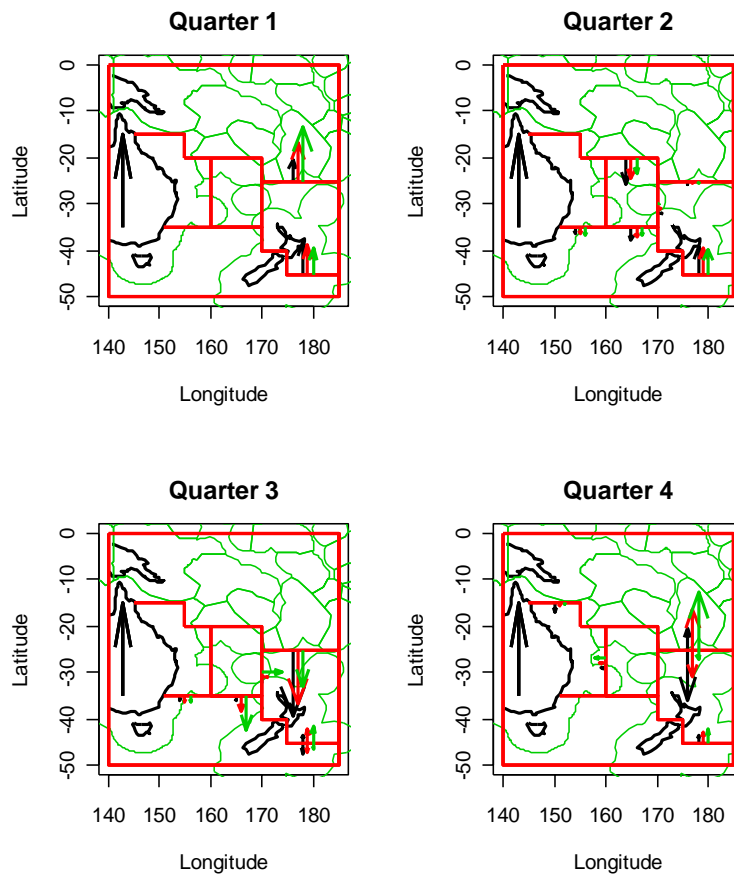


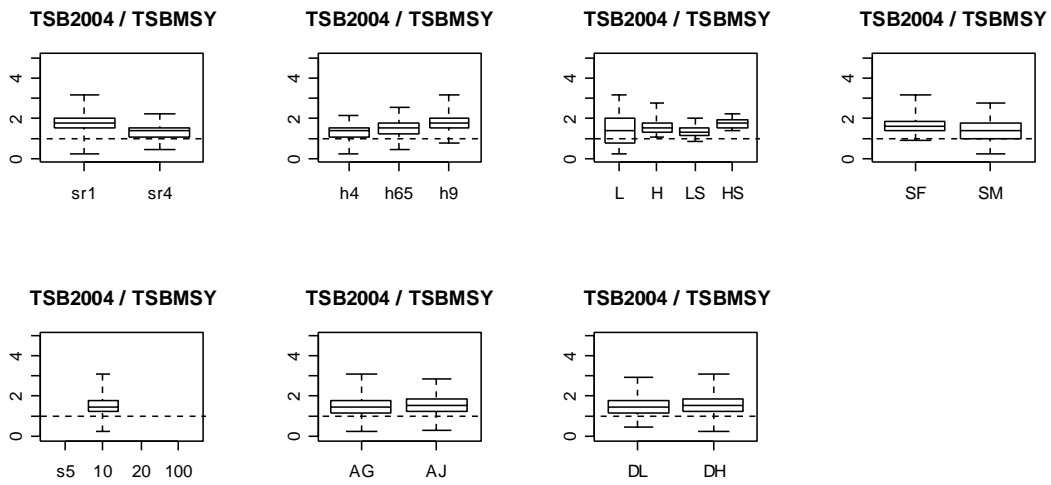
Figure 23. Aggregate fishing mortality for the two example models. Aggregate  $F$  is defined as  $(\text{total catch mass in year } t)/(\text{total stock biomass in year } t)$ .



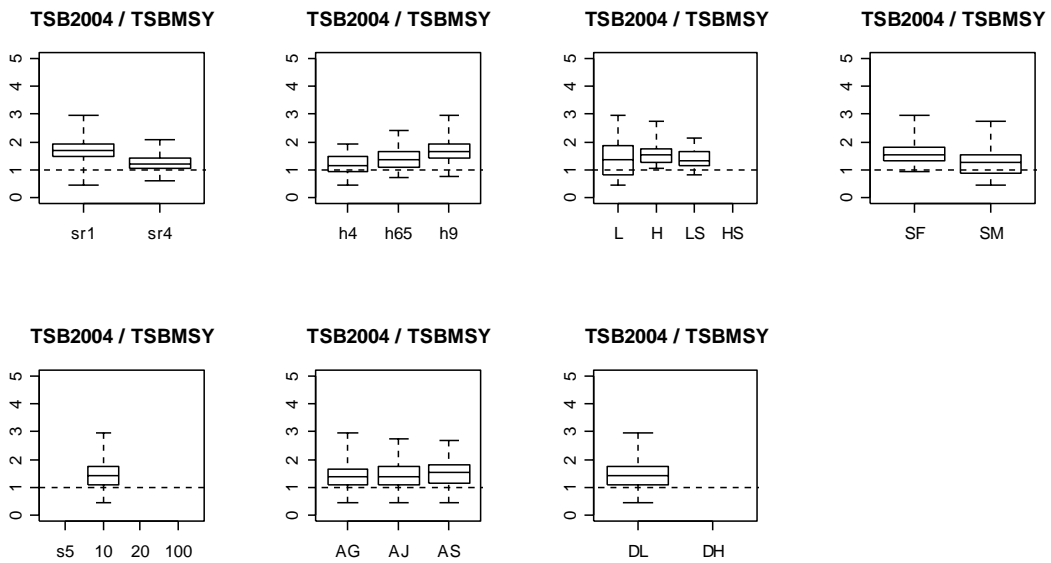
**Figure 24. Estimated Migration patterns for example model 1. Scale bar on Australian continent indicates migration parameter value of 1. Black (bottom or left) arrows correspond to age 4 fish, red arrows age 11 and green age 16.**



**Figure 25. Estimated Migration patterns for example model 2. Scale bar on Australian continent indicates migration parameter value of 1. Black (bottom or left) arrows correspond to age 4 fish, red arrows age 11 and green age 16.**

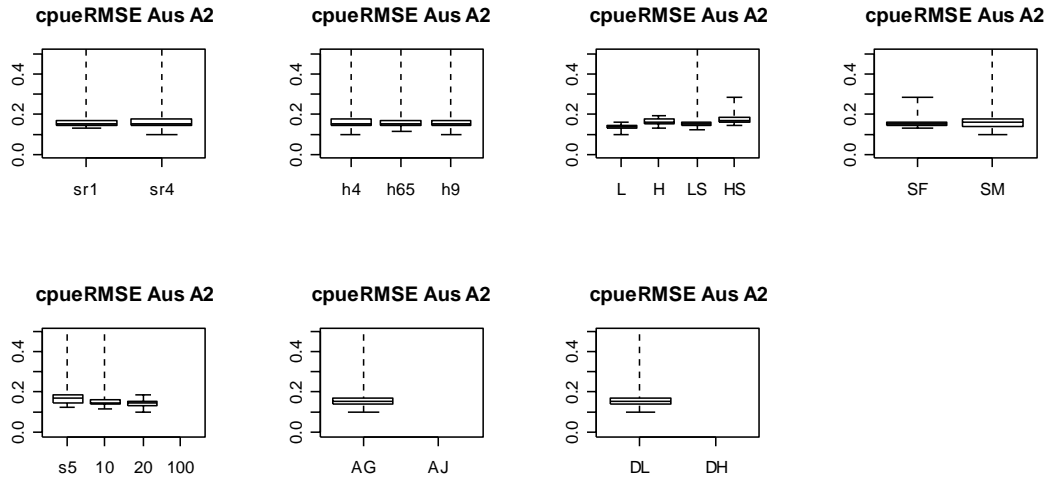


**Figure 26.** MPD estimates of TSB(current)/TSB(MSY) from model combination A with the down-weighted size sample option (s100) removed. Each panel represents a boxplot of the indicated quantity. Within each panel, all results are represented, but partitioned according to the factor labels indicated on the X-axis and defined in Table 4.

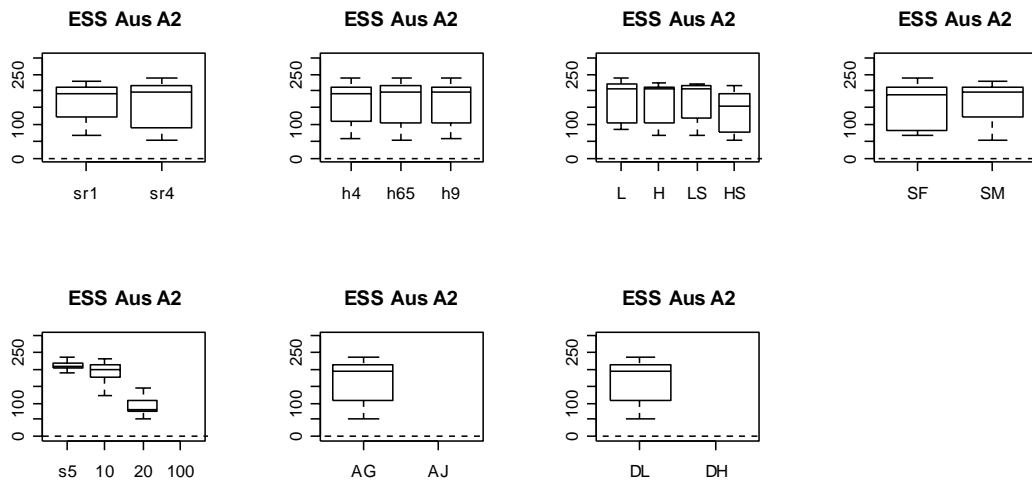


**Figure 27.** MPD estimates of TSB(current)/TSB(MSY) from model combination A2, illustrating that the effective area assumptions (AG, AJ, AS) seem to have the least effect on management implications. Each panel represents a boxplot of the indicated quantity. Within each panel, all results are represented, but partitioned according to the factor labels indicated on the X-axis and defined in Table 4.

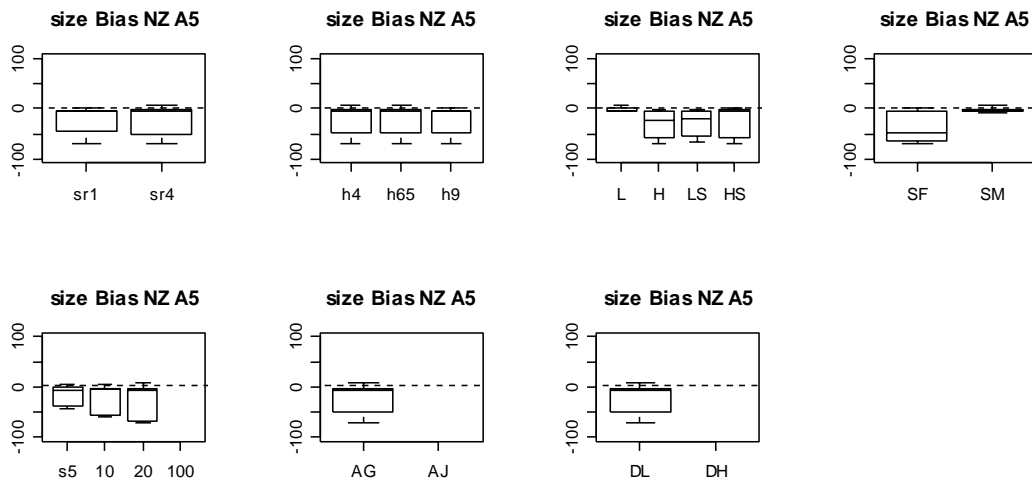




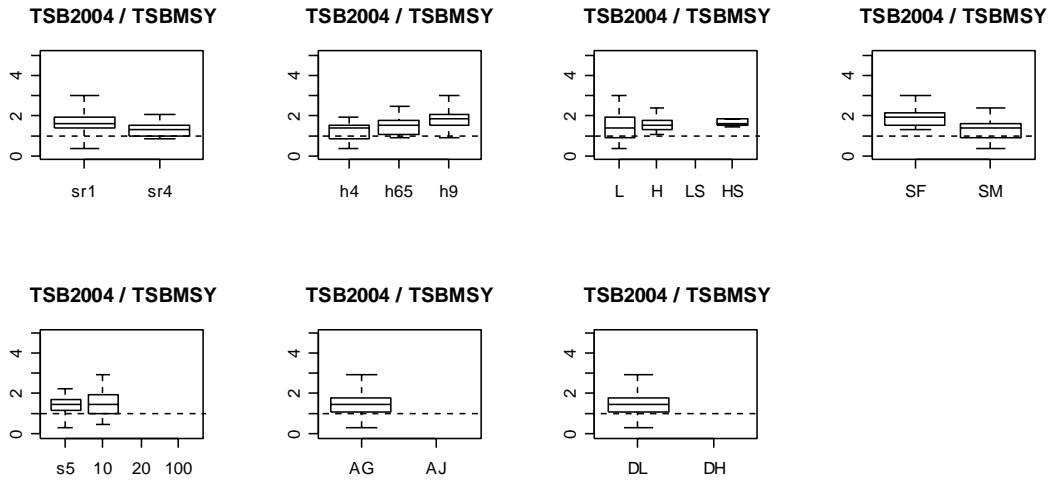
**Figure 28. Quality of fit between predicted and observed CPUE for Aus fishery 2 on the basis of Root Mean-Squared Error. Each panel represents a boxplot of the indicated quantity calculated at the MPD for model combination C listed in Table 6. Within each panel, the results are partitioned according to the factor labels indicated on the X-axis and defined in Table 4.**



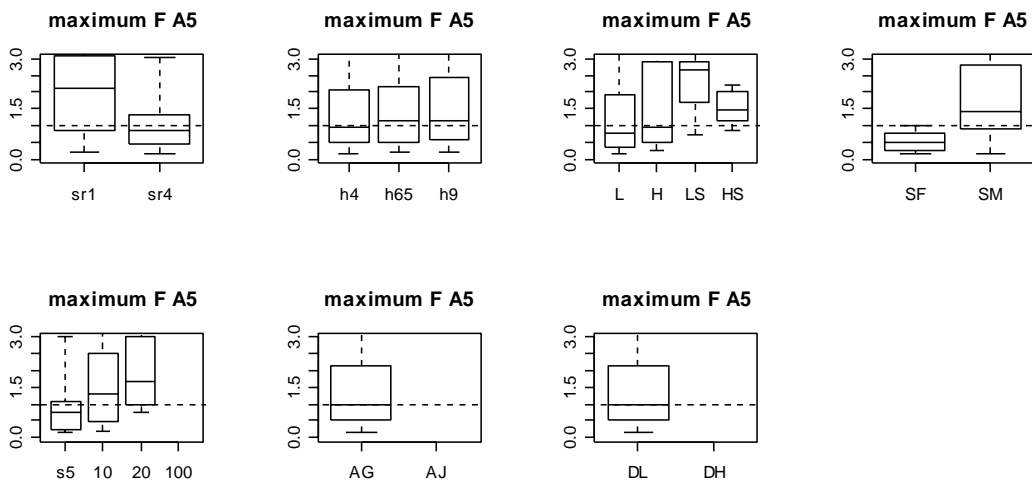
**Figure 29.** Measure of the mean quality of fit for the inshore Australian fishery (the fishery with the best sampling data). The Effective Sample Size (ESS defined in the text), is an approximate measure of the average random sample that would provide a degree of fit between observations and predictions equivalent to the model result. Each panel represents boxplots of the indicated quantity calculated at the MPD for model combination C listed in Table 6. Within each panel, the results are partitioned according to the factor labels indicated on the X-axis and defined in Table 4



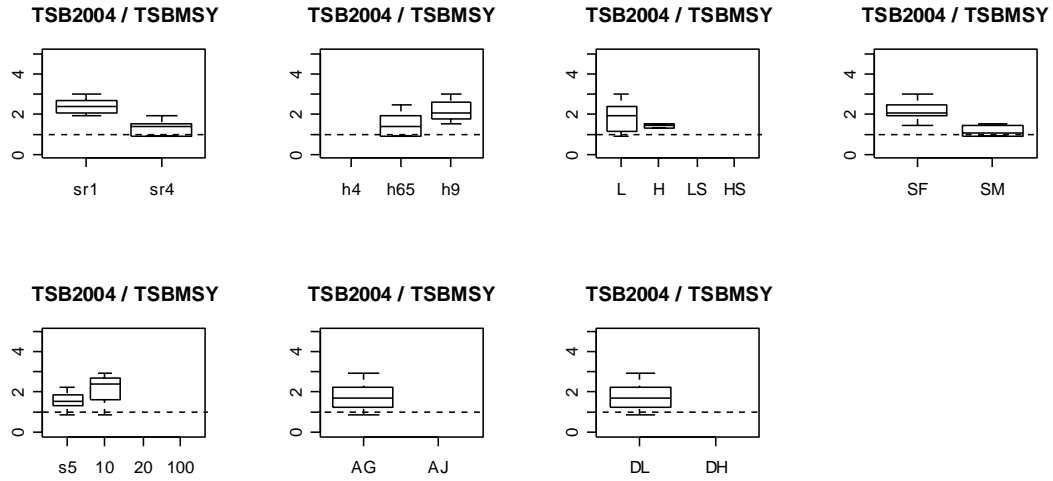
**Figure 30.** Bias (predicted – observed mean length (cm)) in the size composition for the southern NZ fishery. Each panel represents boxplots of the indicated quantity calculated at the MPD for all of the for model combination C listed in Table 6. Within each panel, the results are partitioned according to the factor labels indicated on the X-axis and defined in Table 4.



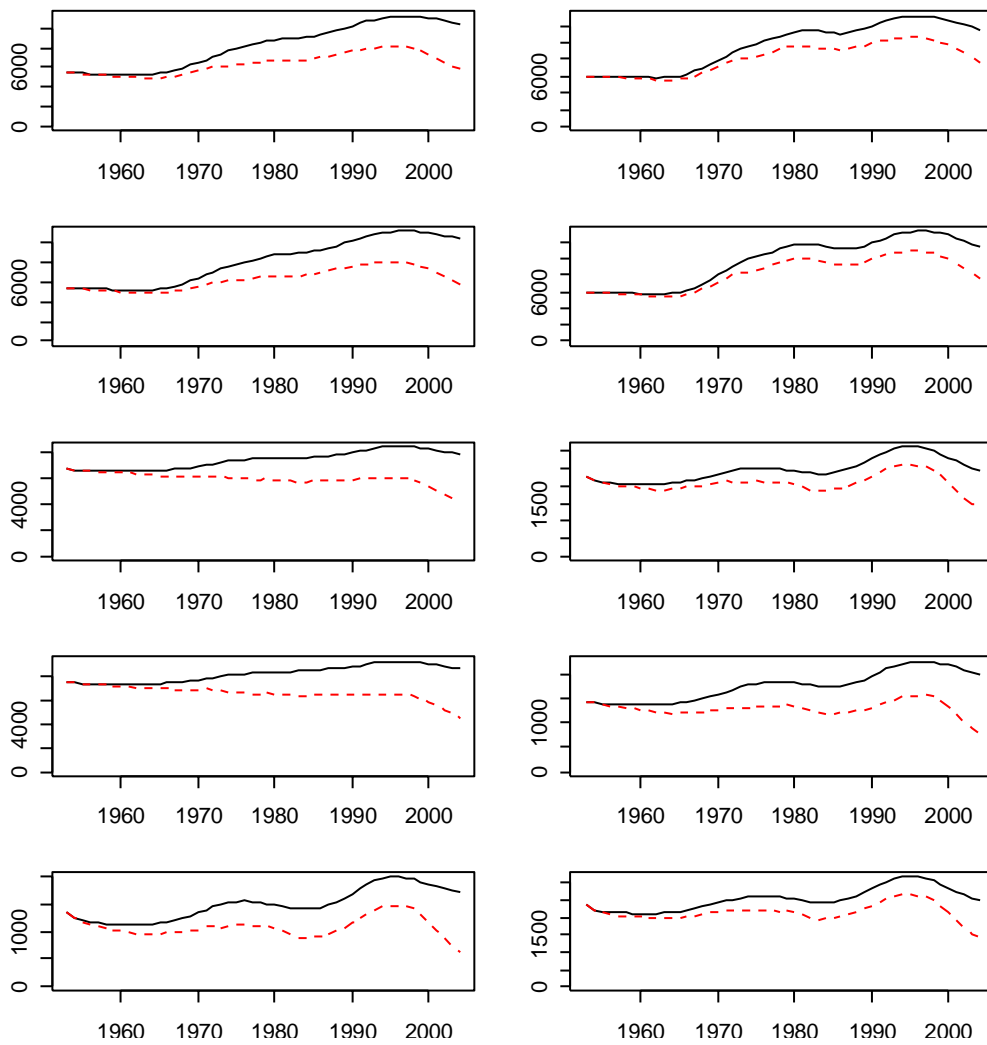
**Figure 31.** MPD estimates of  $TSB(\text{current})/TSB(\text{MSY})$  from model combination D (44 model subset of C meeting minimum convergence, CPUE and size fit criteria). Each panel represents a boxplot of the indicated quantity. Within each panel, all results are represented, but partitioned according to the factor labels indicated on the X-axis and defined in Table 4.



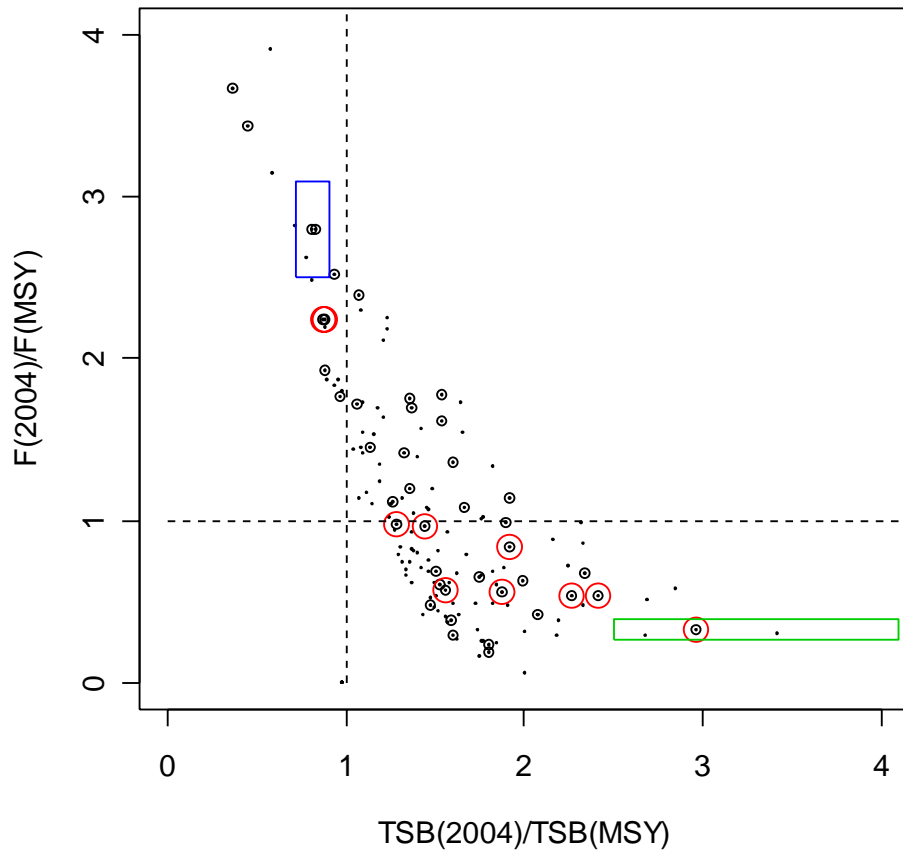
**Figure 32.** Maximum fishing mortality (any age class in any quarter) for Area 5. Each panel provides boxplots of the indicated quantity for model combination C listed in Table 6. Within each panel, all results are represented, but partitioned according to the factor labels indicated on the X-axis and defined in Table 4.



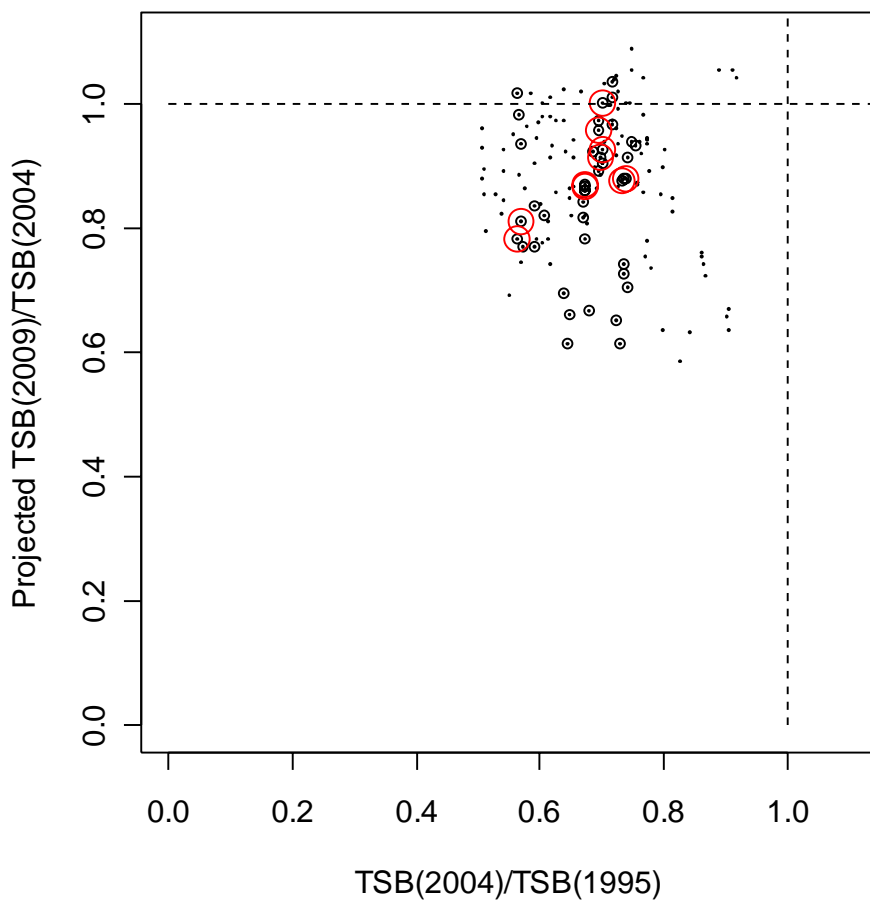
**Figure 33. MPD estimates of TSB(current)/TSB(MSY) from model combination E (10 model subset of C meeting minimum convergence, CPUE and size fit criteria, maximum F and minimum steepness assumptions). Each panel represents boxplots of the indicated quantity for model combination D listed in Table 6. Within each panel, all results are represented, but partitioned according to the factor labels indicated on the X-axis and defined in Table 4.**



**Figure 34. Estimated SSB trends from the MPD estimates of the plausible model ensemble. Broken (red) line is the estimated biomass ( $t$ ), and the solid black line is the estimate of what would have been observed in the absence of fishing.**



**Figure 35. Stock status summary plot. Points indicate the MPD estimates corresponding to model combination C, small circles indicate combination D (subset of C that meets minimum CPUE and size fit criteria), and large (red) circles indicate the most plausible model ensemble (combination E, which is the subset of D that also includes fishing mortality and stock recruitment curve steepness constraints). Example model 1 (blue) and 2 (green) are indicated by the large rectangles which encompass the 95% confidence limits (but not correlation) estimated from the inverse Hessian approximation.**



**Figure 36. Summary of recent biomass trends and short term deterministic projections (with 2004 effort) in relation to model uncertainty. Points indicate the MPD estimates corresponding to model combination C, small circles indicate combination D (subset of C that meets minimum CPUE and size fit criteria), and large (red) circles indicate the most plausible model ensemble (combination E, which is the subset of D that also includes fishing mortality and stock recruitment curve steepness constraints).**

## Appendix 1 – Batch file indicating 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.

---

```
#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
# mfclopt switch_frqA SWO5P001.ini 00.par -makepar
#fi
# -----
# PHASE 1 - initial par
# -----
#
if [ ! -f 01.par ]; then
#switch
#relative area weighting
mfclopt SWOGridAG001.frq
mfclopt SWOGridAJ001.frq
mfclopt SWOGridAS001.frq
#diffusion priors and mortality vectors are specified from input files
00.GridLDL.inpar 01.par -file -<<PHASE1
00.GridHDL.inpar 01.par -file -<<PHASE1
00.GridLSDL.inpar 01.par -file -<<PHASE1
00.GridHSDL.inpar 01.par -file -<<PHASE1
00.GridLDH.inpar 01.par -file -<<PHASE1
00.GridHDH.inpar 01.par -file -<<PHASE1
00.GridLSDH.inpar 01.par -file -<<PHASE1
00.GridHSDH.inpar 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 1
-4 24 1
-5 24 2
-6 24 1
-7 24 1
-8 24 1
-9 24 1
-10 24 2
-1 29 1 #group catchabilities to prevent weirdness (deviations ?)
```



```

-2 29 1 #group catchabilities
-3 29 1 #group catchabilities
-4 29 1 #group catchabilities
-5 29 1 #group catchabilities
-6 29 2 #group catchabilities
-7 29 2 #group catchabilities
-8 29 2 #group catchabilities
-9 29 2 #group catchabilities
-10 29 3 #group catchabilities
-1 60 1 #group catchabilities to prevent weirdness (averages ?)
-2 60 1 #group catchabilities
-3 60 1 #group catchabilities
-4 60 1 #group catchabilities
-5 60 1 #group catchabilities
-6 60 2 #group catchabilities
-7 60 2 #group catchabilities
-8 60 2 #group catchabilities
-9 60 2 #group catchabilities
-10 60 3 #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
mfclopt SWOGridAG001.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 1 500 # 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
mfclopt SWOGridAG001.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
mfclopt SWOGridAG001.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
mfclopt SWOGridAG001.frq 04.par 05.par -file - <<PHASE5
1 16 0 # estimate length dependent SD (I3=1)
PHASE5
fi
# -----
# PHASE 6
# -----

```

```

if [ ! -f 06.par ]; then
mfclopt SWOGridAG001.frq 05.par 06.par -file - <<PHASE6
### 1 14 1 # estimate K
1 141 0 # sets likelihood function for LF data to mod chi2
PHASE6
fi
# -----
# PHASE 7
# -----
if [ ! -f 07.par ]; then
mfclopt SWOGridAG001.frq 06.par 07.par -file - <<PHASE7
### 1 173 8 # estimate independent mean lengths for 1st 8 age classes
### 1 182 10 # penalty weight for deviations xxx dk note - not documented???
-1 10 0 # estimate catchability time series
-2 10 0 # estimate catchability time series
-3 10 0 # estimate catchability time series
-4 10 0 # estimate catchability time series
-5 10 0 # estimate catchability time series
-6 10 0 # estimate catchability time series
-7 10 0 # estimate catchability time series
-8 10 0 # estimate catchability time series
-9 10 0 # estimate catchability time series
-10 10 1 # estimate catchability time series
-1 23 999 # and do a random-walk step every 999+1 months
-2 23 999
-3 23 999
-4 23 999
-5 23 999
-6 23 999
-7 23 999
-8 23 999
-9 23 999
-10 23 2 # and do a random-walk step every 23+1 months
-10 15 1 # relax qTS on f=10 as much as possible
PHASE7
fi
# -----
# PHASE 8
# -----
if [ ! -f 08.par ]; then
mfclopt SWOGridAG001.frq 07.par 08.par -file - <<PHASE8
# -999 27 1 # estimate seasonal catchability for all fisheries
# 1 14 0 # de-activate K for the time being
-1 13 -1 # effort dev weighting (neg = sqrt transformed)
-2 13 -1 # effort dev weighting (neg = sqrt transformed)
-3 13 -1 # effort dev weighting (neg = sqrt transformed)
-4 13 -1 # effort dev weighting (neg = sqrt transformed)
-5 13 -1 # effort dev weighting (neg = sqrt transformed)
-6 13 100 # effort dev weighting (neg = sqrt transformed) 100 over 10 = CV 0.15
-7 13 100 # effort dev weighting (neg = sqrt transformed)
-8 13 100 # effort dev weighting (neg = sqrt transformed)
-9 13 100 # effort dev weighting (neg = sqrt transformed)
-10 13 -1 # effort dev weighting (neg = sqrt transformed)
PHASE8
fi
# -----
# PHASE 9
# -----
if [ ! -f 09.par ]; then
mfclopt SWOGridAG001.frq 08.par 09.par -file - <<PHASE9
2 27 1 # relax migration prior weight I3 over 10 (default is 50 over 10)
2 68 1 # on estimate movement coefficients #manual says activates movement
2 69 1 # on sets generic movement option (now default) #manual says estimates movement params
#switch
-999 16 1 #selectivity non-decreasing with age
-999 16 0 #selectivity free
PHASE9
fi
# -----
# PHASE 10
# -----
if [ ! -f 10.par ]; then
mfclopt SWOGridAG001.frq 09.par 10.par -file - <<PHASE10
2 33 0 # estimate mean natural mortality rate (devs can be imposed in 0.par)
PHASE10

```

```

fi
# -----
# PHASE 11
# -----
if [ ! -f 11.par ]; then
mfclopt SWOGridAG001.frq 10.par 11.par -file - <<PHASE11
  2 88 1 # activate parameters
  2 89 1 # and estimate age-dependent movement
PHASE11
fi
# -----
# PHASE 12
# -----
if [ ! -f 12.par ]; then
mfclopt SWOGridAG001.frq 11.par 12.par -file - <<PHASE12
# 2 73 1 # estimate age-sepdependent M
# 2 77 1 # estimate age-sepdependent M second diff pen (default=25)
# 2 78 1 # estimate age-sepdependent M first diff pen (default=5)
# 2 79 10 # estimate age-sepdependent M dev from mean pen (default=10)
  2 145 1 # estimate Beverton Holt SRR with small penalty
  2 146 1 # SRR parameter active
  2 147 1 # recruitment lag is 1 quarter
  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)


---


#switch
# parameters of beta distribution defining prior for
# steepness - mode = (153 flag over (153 flag + 154 flag), sd approaches 0 as flags get big)
2 153 4000 2 154 6000
2 153 6500 2 154 3500
2 153 9000 2 154 1000


---


PHASE12
fi
# -----
# PHASE 13
# -----
if [ ! -f 13.par ]; then
mfclopt SWOGridAG001.frq 12.par 13.par -file - <<PHASE13
### 1 14 1 # estimate von Bertalanffy K
  2 107 0 # off- turn on exploitation rate target
  2 108 0 # off- set exploitation rate target as x% (Catch(numbers) over Rec(N))
#1 149 31 # set penalty on recruitment devs to n over 10 (500 over 10 ~ cv of 0.1; 14 over 10 ~ 0.6; 31~0.4)
  1 149 1 # set penalty on recruitment devs to n over 10 (500 over 10 ~ cv of 0.1; 14 over 10 ~ 0.6; 31~0.4)
  2 145 50 # 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)
#-100000 1 1 # est rec in region I3 # THIS WORKS AS A GROUP
#-100000 2 1 # est rec in region I3
#-100000 3 1 # est rec in region I3
#-100000 4 1 # est rec in region I3
#-100000 5 1 # est rec in region I3
  2 113 0 # shut off estimate initpop over totpop scaling parameter
  1 1 1000 # set no. function evaluations
  1 50 -3 # set convergence criterion to 1En
PHASE13
fi
# -----
# PHASE 14
# -----
if [ ! -f 14.par ]; then
mfclopt SWOGridAG001.frq 13.par 14.par -file - <<PHASE14
# 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 ???


---


#switch
#size sample downweighting
-999 49 5 -999 50 5
-999 49 10 -999 50 10
-999 49 20 -999 50 20
-999 49 100 -999 50 100


---


#switch
#recruitment deviations from SR
2 145 3

```

```

2 145 50
2 145 3
1 1 1000 # set no. function evaluations
1 50 -3 # set convergence criterion to 1En
PHASE14
fi
# -----
# PHASE 15
# -----
if [ ! -f 15.par ]; then
mfclopt SWOGridAG001.frq 14.par 15.par -file - <<PHASE15
# -100000 1 1 # estimate
# -100000 2 1 # time-invariant
# -100000 3 1 # distribution
# -100000 4 1 # of
# -100000 5 1 # recruitment
# -100000 6 1
# -100000 7 1
# -999 48 0 # de-activate selectivity estimation
1 1 1000 # 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
PHASE15
fi
# -----
# PHASE 16
# -----
if [ ! -f 16.par ]; then
mfclopt SWOGridAG001.frq 15.par 16.par -file - <<PHASE16
# 1 149 0 # reduce pens on devs from av. recr (to avoid 2 penalties)
-999 55 1 # compute biomass with catchability for all fisheries set to 0
1 1 3000 # set no. function evaluations
PHASE16
fi
# -----
# PHASE 17+ in first instance this is shut off for speed... hess calc errors possible too...
# -----
#switch_frqAOnly
#16.par -file - <<PHASE17
# 1 145 3 # set output level 3 for Hessian calc
# 1 189 0 # off write length.fit and weight.fit (obs. and pred. LF data)
# 1 190 0 # off write plot.rep
#PHASE17
#switch_frqA
#16.par -file - <<PHASE18
# 1 145 4 # set output level 4 for std
#PHASE18
#switch_frqA
#16.par -file - <<PHASE19
# 1 145 5 # set output level 4 for .var; 5 = .cor
#PHASE19
mv 16.par sr1_h4_H_SF_CL5_AG_DH.outpar
mv plot.rep sr1_h4_H_SF_CL5_AG_DH.rep
mv length.fit sr1_h4_H_SF_CL5_AG_DHlength.fit
mv weight.fit sr1_h4_H_SF_CL5_AG_DHweight.fit

```