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CASAL Stock Assessment for South-West-Central Pacific Broadbill Swordfish 1952-2007

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Nick Davies [1, 2]
Richard Bian [1]
Dale Kolody [3]
Robert Campbell [4]

[1]National Institute of Water and Atmospheric Research Ltd, Auckland, New Zealand
[2](currently at) Secretariat of the Pacific Community, Noumea, New Caledonia
[3]CSIRO Marine and Atmospheric Research, Hobart, Australia
[4]CSIRO Marine and Atmospheric Research, Aspendale, Australia

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Executive Summary

Swordfish catches in the south-west-central Pacific region increased from the low levels recorded in 1952 to around 30 000 fish per year in 1970, with catches taken mainly by the Japanese and distant water fleets from other nations. After a brief decline in the mid-1970's, catches remained stable at around 30 000 fish per year until the mid-1990s. Regional catches rapidly increased after 1994 due to the development of the domestic longline fisheries in Australia at first, and then in New Zealand. From 2001 to 2005, regional swordfish catch was, on average, 116,000 fish per year, or 6500 t.

A CASAL stock assessment of south-west Pacific swordfish was undertaken in 2006 and presented to WCPFC-SC 2. The consideration of model uncertainty was incomplete, in particular that relating to spatial processes. Under WCPFC-CMM 06-3, an updated assessment was requested for presentation in 2008 that incorporates new tagging information to address spatial uncertainty, and extends the model domain to include the south-central Pacific Ocean. The assessment presented here updates the 2006 model, with substantial changes to structural assumptions for spatial disaggregation, movement, and fishery definitions. These structural changes were made on the basis of new information on fish movement from satellite archival tagging data, but also a review of catch and effort data. Two of the four areas defined in the model encompass the same domain assumed for the 2006 assessment. Areas 3 and 4 extend this domain eastwards to include the south-central Pacific Ocean from 175°W to 130°W. Models were developed under three alternative spatial options for area combinations:
- areas 1 and 2 (2ar)
- areas 3 and 4 (4ar), and,
- areas 1 to 4 (1_4ar).

The CASAL swordfish population model for the south-west-central Pacific region was fitted to catch-per-unit effort and catch-at-length observations collated from all the regional fisheries. Structural and statistical uncertainty was estimated using a grid design for factors including: spawning stock-recruitment relationship (SRR), growth, mortality- and maturity-at-age schedules, migration, fishery definitions, and relative weight of catch-at-size and CPUE data. Model plausibility criteria were calculated following the approach of Kolody et al. (2006). This assessment draws strongly from

the advice from an Open Workshop held in April 2008 (Anon 2008) and supports a parallel assessment developed using Multifan-CL (MFCL) by Kolody et al. (2008). Derived quantities from model estimates described stock status in terms of relative change in biomass, total and spawning stock abundance relative to the MSY reference point level.

From the 256 models for the 2ar spatial option obtained from the grid design of uncertainty factors, a most plausible model subset of 103 was identified. Implausible models were characterised by a generally poorer quality of fit, spiked selectivity functions, but mostly by exceptionally high absolute abundance estimates; 1 order of magnitude higher than the large mode depicted by the 103 model subset. Models were considered in respect of the data conflicts apparent, and the practicality of the high abundance estimates. There was no clear basis for specifying model implausibility in respect of the quality of fit associated with particular uncertainty factors. Rather, models with extremely high abundance were deemed implausible because: mean recruitment estimates were close to, or at, the upper bounds; total biomass estimates were unrealistically high, i.e., of a similar order to the large tuna stocks that support fisheries producing nearly 100-fold higher catches annually; and, estimated fishing impacts were around 1-2% and this contrasts strongly with independent studies suggesting local depletion in the Australian fishery.

High variability in the derived quantities of stock status was attributed to structural and function minimisation problems. Assumptions made for statistical specifications and for many of the parameters included in the uncertainty grid design determined variability in the derived quantities and revealed data conflicts. Of the uncertainty factors tested, those less prevalent in the 103 model subset included the options for steepness of 0.65, slow growth rates, and low relative weight for CPUE from DP and DW fisheries, indicating that these factors were more associated with less plausible models. Trends in recent total biomass were less variable for models assuming high relative weight for the AU and NZ CPUE data. Models assuming low SRR steepness, slow growth and high relative weight for the DP and DW CPUE time series produced lower estimates of population abundance relative to the MSY level, and higher current exploitation rate relative to F_{MSY}; i.e., were more pessimistic of current stock status. These models predict a population having characteristically lower productivity, and hence lower resilience. This feature was reflected in stock projections where these assumed uncertainty factor options produced lower, and less variable, predicted abundance relative to current levels.

The swordfish population biomass in areas 1 and 2 is predicted to have declined dramatically since 1952 to a relatively low level in 2005 (median value of around 35% of the 1952 level) with a subsequent increase, due to above average recent recruitments since 2004-05. Model projections show that, with a return to average recruitments, the increase in stock size asymptotes at around 45% of the 1952 level. A substantial decline (38%) in total biomass was predicted over the past 10 years. Over the next 5 years total biomass is predicted to increase by 18.5% but will remain below, at 76% of, the historical (1997) level.

The estimates of stock status relative to B_{MSY} and F_{MSY} were highly variable and the median for the derived quantity TSB(2007)/TSB(MSY) is lower than the MFCL estimate (1.26 versus 1.57) and this reflects fundamental differences between the

parallel assessments. Four main differences between the MFCL and CASAL assessments were identified that make direct comparisons between the results difficult:
1) CPUE time series included in the model fit,
2) fishery selectivities estimated,
3) CASAL function minimisation problems, and,
4) CASAL formulation of MSY-related derived quantities.

The MFCL assessment assumed the DP and DW CPUE time series in zone 2 of areas 1 and 2 were indicative of relative abundance, and excluded the series in zones 1 and 3 from the model fit. This difference in the statistical assumptions between the two assessment models was examined for a small subset of CASAL models. The effect of the assumption made for the MFCL model was primarily to reduce variability in derived quantities.

The CASAL model estimated 20, or more, selectivity functions compared to the 4 estimated for the MFCL model. While improving the fit to seasonality in observed CPUE and catch-at-size, and serving to proxy for temporal and latitudinal movement processes, this higher number of parameters would have increased the uncertainty in CASAL derived quantities.

A significant problem for the CASAL assessment was model function minimisation problems, in that there was a clear indication for the lack of convergence on a global minimum. This was revealed by a simple test using two similarly-specified models that produced widely divergent absolute abundance estimates. Model estimates were highly sensitive to the initial parameters assumed for fitting to the observations. The median values of derived quantities may therefore not necessarily be associated with solutions from global minima of the objective function. This source of uncertainty limits the depth of interpretation possible from the CASAL results, particularly for absolute abundance estimates.

CASAL model estimates of current abundance relative to the MSY-related reference point level were necessarily expressed in terms of numbers of fish rather than biomass. This was because of a structural assumption for a “weightless model” required in order to fit to the observations that were expressed in terms of numbers of fish rather than biomass. The ratio of current estimates of abundance in numbers relative to MSY-related derived quantities will differ from that expressed in terms of biomass because of the change in mean weight with respect to population size and equilibrium status. Consequently, when current abundance is above that at the MSY level (B_{MSY}), the ratio of current abundance to B_{MSY} will be lower when expressed in terms of numbers than in biomass. As such, the MSY-related derived quantities for the CASAL model will be more pessimistic compared to those for the equivalent quantity expressed in biomass.

The median current biomass relative to the estimated unexploited level for TSB and SSB, was 39% and 20% respectively. These quantities are more pessimistic than the MFCL estimates (0.58 and 0.43 respectively).

While good fits were made to many of the observations for the 2ar spatial option, the CASAL model selectivity estimates for the DP, DW and PN fleets were often implausible (spiked), and the estimates of absolute stock size and current status were variable, such that the predicted estimates of current stock status from the more plausible model runs spanned the range of potentially overfished and underfished states. However, the model did provide consistent predictions of recent population declines, e.g., between 37% and 79% decline in spawning biomass since 1997. CASAL derived quantities for relative change in biomass were broadly consistent with those of the parallel MFCL assessment. However, the function minimisation problems exhibited in the CASAL model means that other derived quantities are highly uncertain. The MFCL modelling approach that utilises a phasing estimation procedure, minimises the potential for producing solutions associated with local minima. Hence, the stock status estimates from the parallel assessment using MFCL may be more reliable than those presented here. Additionally, the MFCL assessment reports estimates of stock status in conventional terms (in respect of biomass), and may therefore be more easily interpreted by managers.

Among the 256 combinations of uncertainty factors tested for the 4ar spatial option, none produced mean recruitment parameter estimates that were below the upper bound, or were plausible model estimates. Over the range of models tested, there was no indication of convergence towards an estimated distribution for absolute abundance. This suggests that overall there was insufficient information available for estimating population abundance and this result supports the view expressed at the Open Workshop for the 2008 swordfish assessment in regards stock structure and data available. The paucity of catch-at-size data from areas 3 and 4 combined with an uncertain CPUE time series exhibiting an increasing trend from the northern zone only, offers limited information for estimating the relatively large number of CASAL model parameters. The results were similar for attempts to fit a model over areas 1 to 4 (spatial option 1_4ar), where clear conflicts between the CPUE time series in areas 1 and 2, versus, areas 3 and 4 were apparent. Consequently, the status of the swordfish stocks in the south-central Pacific Ocean could not be estimated from this assessment.

The updated CASAL assessment model thoroughly explores sources of structural uncertainty. However, a limitation to making stock status interpretations is the function minimisation problem. To take more value from the CASAL assessment model, it is recommended that the cause of function minimisation problems be identified and the estimation of parameters in separate phases be developed.

Introduction

Swordfish is a widely distributed species and is found throughout the Pacific Ocean (i.e. appears in longline catches) from 50º N to 50 º S in the western Pacific Ocean and 45º N to 35º S in the eastern Pacific Ocean. Genetic studies indicate the worldwide population of swordfish is genetically structured not only between the major oceans, but also within each ocean, and that gene flow is restricted despite the absence of geographic barriers (Chow et al. 1997, Reeb et al. 2000). For the Pacific Ocean there is recent evidence for distinct populations between the north-east and south-east regions, and between south-west and south-east regions, although the boundary for the southern regions is uncertain (Alvarado Bremer et al. 2006).

Swordfish catches in the south-west Pacific region from distant water Japanese longline vessels have been recorded since 1952. These catches increased from low levels to around 30 000 fish per year in 1970, and after a brief decline in the mid-1970's, catches remained stable at around 30 000 fish per year until the mid-1990s. At this time foreign licensed fishing for the Japanese fleet to Australian and New Zealand territorial waters ceased, resulting in a decline in the Japanese catch since then. Regional catches have rapidly increased since 1994 due to the dramatic expansion of the Australian domestic longline fishery that targets swordfish (Murray & Griggs 2006). During this period, many vessels entered the Australian eastern tuna fishery with subsequent increases in annual effort, and the total catch of swordfish increased dramatically from less than 50 t in 1994 to around 3,080 t in 1999. A corresponding increase occurred in the New Zealand domestic longline fishery. Swordfish catches in the New Zealand domestic tuna longline fishery increased rapidly from a nominal by-catch of less than 100 t in 1993 to around 1000 t per year in 2001 and 2002, but have since declined to around 350 t in 2005. Since October 2004, swordfish was introduced to the New Zealand quota management system (QMS) with a total allowable commercial catch limit (TACC) of 885 t. Catches in 2006 were around 1000 t and 600 t in the Australian and New Zealand longline fisheries, respectively.

Swordfish catches in the south-central Pacific region were relatively low, generally less than 1000 t and taken primarily as a bycatch of the Japanese fishery. After 1985, Korean catches increased steadily while Japanese catches declined, with the total catch in 2000 being over 2000 t. Since 2000, Taiwanese catches increased such that in 2003 total catches were over 4000 t. Concurrent to a subsequent decline in the Taiwanese and Korean catches, there has been a rapid increase in Spanish catches such that the total 2006 catch was again over 4000 t. Currently, catches in the south-central Pacific region exceed those taken in the south-west Pacific, and over both regions, the Spanish catch was the largest component of the total catch in 2006.

In 2006 a stock assessment for south-west Pacific swordfish was undertaken prompted by a number of fishery indicators creating concern for the stock status, including marked declines in catch-per-unit-effort and mean length of fish in catches. Spatially stratified catch rates in the Australian longline fishery indicated systematic declines, and high catch rates were only maintained by extending the grounds each year (Campbell 2002). Therefore, local depletion of swordfish may be possible. The 2006 assessment was undertaken using population models developed using CASAL (C++ algorithmic stock assessment laboratory, Bull et al. 2005) and Multifan-CL, MFCL, (Kleiber et al. 2003) and were presented to WCPFC-SC 2. The consideration of model uncertainty for the CASAL model (Davies et al. 2006) was incomplete, in particular that relating to spatial processes. Therefore, advice from the assessment was based upon the MFCL results (Kolody et al. 2006). Under WCPFC-CMM 06-3, an updated assessment was requested for presentation in 2008 that incorporates new tagging information to address spatial uncertainty, and extends the model domain to include the south-central Pacific Ocean.

The assessment presented here updates the 2006 CASAL model, with substantial changes to structural assumptions for spatial disaggregation, movement, and fishery definitions. These structural changes were made on the basis of new information on fish movement from satellite archival tagging data, but also an updated review of catch and effort data. Two of the four areas defined in the model encompass the same domain assumed for the 2006 assessment. Areas 3 and 4 extend this domain eastwards to include the south-central Pacific Ocean from 175°W to 130°W. Structural and statistical uncertainty was estimated using a grid design for factors including: spawning stock-recruitment relationship (SRR), growth, mortality- and maturity-at-age schedules, migration, fishery definitions, and relative weight of catch-at-size and CPUE data. This approach for estimating uncertainty and the calculated model plausibility criteria follows that used by Kolody et al. (2006) for the 2006 assessment, and applied again in 2008 (Kolody et al. 2008). Derived quantities from model estimates described stock status in terms of relative change in biomass, total and spawning stock abundance relative to the MSY reference point level. This assessment draws strongly from the advice from an Open Workshop held in April 2008. As in 2006, this assessment supports a parallel assessment undertaken using MFCL (Kolody et al. 2008).

Methods

Model specifications

The CASAL age-structured population model used for estimating south-west Pacific swordfish abundance and yield in 2006 (Davies et al. 2006) was updated and modified for the assessment presented here. The CASAL software framework is described by Bull et al. (2005) and flexibly accommodates alternative structural assumptions. The model was fitted to a time series of standardised catch-per-unit-effort (CPUE) and catch-at-length observations from the tuna longline fisheries.

This assessment supports one developed in parallel by Kolody et al. (2008) using Multifan-CL (MFCL) (Kleiber et al. 2003). To maintain comparability between the two models, where possible the specifications and assumptions made were kept similar.

Given that there was limited sex-specific information available from the regional population and the high uncertainty in swordfish growth, maturity and mortality, it was concluded that developing a sex-structured assessment model would have limited value. Consequently, the model was not sexually disaggregrated.

Spatial disaggregation

A complex multiple area structure was assumed for the 2006 model with specific assumptions made for spawning and foraging site fidelity. These assumptions were revised on the basis of new information from tagging studies, and a consideration of catch-per-unit-effort (CPUE), and catch-at-size data. This review is described by Kolody & Davies (2008) and Kolody et al. (2008), but the main implications for the spatial disaggregation assumed for the 2008 assessment are outlined.

The results of both conventional tag and pop-up satellite archival tag (PSAT) studies did not indicate spawning or foraging site-fidelity, for example in the Coral Sea area. The assumptions associated with this feature were ignored in developing a less complex spatial structure for the 2008 model.

To address the specific details of the WCPFC-CMM 06-3 for swordfish, the 2006 model domain was extended eastwards to 130°W. The 2008 model domain within the southern WCPO was 0-50° S, 140°E-130°W that encompassed the main region of interest for assessing the swordfish stock located within the south-west and south-central Pacific Ocean. Given the spatial distribution of fishing effort of individual fleets and the associated catch of swordfish across this domain, the following 4 area structure was assumed:

- Area 1: 140-165˚E
- Area 2: 165˚E -175˚W
- Area 3: 175˚W -150˚W
- Area 4: 150-130˚W

with three zones defined within each region:

- North: 0-20˚S
- Central: 20-40˚S
- South: 40-50˚S

that provides a reasonable delineation for the fishery definitions across the model domain and by region (Figure 1). This spatial disaggregation was agreed at an Open Workshop for the south-west-central swordfish stock assessment recommending that it:

i) provides compatibility with CMM 06-3,
ii) reduces problems related to representing latitudinal seasonal migration,
iii) is suitably disaggregated to represent differential harvesting in different sub-regions,
iv) can be iteratively revised with different eastward boundaries in relation to evolving opinions about data quality and stock connectivity with the Eastern Pacific Ocean (Anon 2008).

Fisheries

The fisheries operating in the south-west Pacific region were aggregated by nationality, area and zone taking account of the unique characteristics in terms of the total catch by fleet in each zone, and the typical fishing characteristics of each fleet, e.g. hooks per basket; and size compositions (Campbell & Davies 2008). These comparisons were limited by the sample sizes for some fleets within zones. The results indicated similar sized fish between Pacific Island nations, and a combined distant water fleet (including Japan, Taiwan, and Korea), but significant differences remained for some area-zones, though samples were usually small. These differences were inconclusive and suggested that these two fleets could be aggregated. Consequently, two assumptions regarding differences in fishing selectivity between fishing fleets were made in the model, either three or four selectivities were used, defined by nationality as follows:

- Australia (AU);
- New Zealand (NZ),

with either:

- Distant water fleets (DP) including the Japan fleet, and all other distant water fleets, and the Pacific Island Nations' fleet (PN).

or:

- Distant water fleets (DW) including the Japan fleet, distant water fleets from Korea and Taiwan, Spain, Canada, USA, Philippines, and Indonesia

- Pacific Island Nations' fleet (PN).

The option assuming three selectivities was termed the Minimal Fleet option made up of 12 fisheries, and that assuming four selectivities the Extended Fleet option made up of 18 fisheries (Table 1).

Population structure

The following assumptions were made regarding the population structure and biological parameters:

Age classes:	0 to 19+ years; 19+ being an aggregate class
Stock-recruitment:	Beverton-Holt relationship
Annual cycle:	Quarterly time steps
Start year:	1952
End year:	2007
Recruitment:	One event per year at the beginning of quarter 1
Recruitment distribution:	Distributed uniformly among areas
Length-weight:	$w = a(l^b)$, length (cm), trunked weight (kg)
	a = 7.62e-7 b = 3.49

Although length-weight parameters were used to express the population state in terms of biomass as required for certain output quantities, the model is specified as being weightless, i.e., all calculations are made in respect of numbers of individual fish. This is because all input observations for catches, catch-at-size and CPUE were available in terms of numbers of fish only. Conversions from numbers at length to biomass were calculated outside of the model.

Other biological parameters (recruitment, growth, mortality, maturity) are described later in respect of model uncertainty.

Fishing mortalities were calculated for the various longline fishing fleets using the separability assumption (Fournier & Archibald 1982, Deriso et al. 1985, Methot 1990) using method-specific selectivity-at-length patterns and the reported catch in numbers. An instantaneous exploitation rate catch equation was used and the maximum rate for an age class in a fishery was 0.7.

Regional input data

The regional data input to the 2008 swordfish assessment was reviewed at an Open Workshop SPC, April 2008 (Anon 2008), and has been described by Kolody et al. (2008) and Campbell (2008) as input to the MFCL and CASAL parallel assessments. A brief outline follows of main components of these data.

Annual catches

Catch statistics from all fisheries operating in the south-west Pacific region were provided by the Secretariat of the Pacific Community (SPC) from data reported to the Western and Central Pacific Fisheries Commission (WCPFC), and are administered by SPC on their behalf. Swordfish catch is reported as the frequency caught, i.e., numbers of fish caught per area and quarter. Campbell & Davies (2008) and Campbell (2008) describe the catch and effort data input to this assessment that covers the years 1952-2006 for all fleets and for each fleet.

The total catches by nation over all areas are presented in Figure 2. Total annual catches in areas 1 and 2 were relatively stable at around 25 000 to 30 000 swordfish up to 1995 mainly as a bycatch of the Japanese longline fishery. This increased dramatically after 1996 due to the rapid expansion of the Australian and New Zealand fisheries, to a maximum annual catch in 2002 of over 70 000. The catch has since declined to around 40 000 in 2006. Total catch in areas 3 and 4 was relatively low, around 5 to 10 000 fish taken primarily as a bycatch of the Japanese fishery until 1985, after which Korean catches increased steadily while Japanese catches declined. Since 2000 Taiwanese catches increased such that in 2003 total catches peaked at over 75 000 fish. Concurrent to a subsequent decline in the Taiwanese and Korean catches, there has been a rapid increase in Spanish catches such that the total 2006 catch was around 62 000 swordfish. Over areas 1 to 4, the Spanish catch was the largest component of the total catch.

The catch data extended to 2006 for all fleets except one, for which the catch was taken from operational logbook data that was assessed to be more than 90% complete. In order to utilise recent available CPUE and catch-at-size observations, the catch time series was extended to 2007 under certain assumptions. Operational logbook data was used for the Australian and New Zealand fisheries, while for all other fisheries the catch in each quarter in 2007 was set equal to the catch in the equivalent quarter in 2006.

Fishery CPUE

The standardised CPUE time series used for the 2006 assessment model were reviewed according to the 2008 model spatial structure and fisheries definitions (Campbell et al. 2008). For the DP and DW fisheries, the Japanese standardised indices were assumed. For areas 3 and 4 there was only sufficient data to derive indices for the two northern regions (3-N, 4-N). Due to there being scant data available in region 3-N with extremely little coverage for two quarters, the CPUE was expressed in two-quarter blocks (1&4 combined and 2&3 combined).

The years for which quarterly CPUE time series are available for each of the defined fisheries in the minimal and extended fleets are listed in Table 2. The AU fishery indices are for the period - Qtr3 1997 to Qtr 4 2007 – for Area 1 Central Zone only, and the NZ indices are for the period - Qtr1 1998 to Qtr 3 2007 – for Area 2 Central Zone only. The CPUE time series for the fisheries under the minimal fleet options are presented in Figures 3 to 5. All time series for zone C in areas 1 and 2 have a similar pattern for a decreasing trend from 1998 to 2005, followed by a subsequent increase to 2007, although the increase is less pronounced for the DP fishery. The trends in CPUE for areas 3 and 4 contrasted with those in areas 1 and 2, with a steady increase since 1970, that was more pronounced in area 4 (Figure 5).

Catch size compositions

A time series of catch-at-size observations is available for each fishery under the minimal and extended fleet options. The time series extent and sample sizes for each are listed in Table 2. The large sample sizes available for the Australian fishery since 1997 and the New Zealand fishery since 2005 were derived from the individual fish processed weights obtained from fish processing facilities. These processed weights were converted to whole fish lengths using a predictive regression derived from New Zealand scientific observer data.

Model uncertainty

A recommendation from the 2006 CASAL assessment model was to further explore sources of uncertainty. The approach described by Kolody et al. (2006) for estimating structural uncertainty has been followed for this assessment. The rationale and specifications of this approach used for the parallel MFCL assessment (Kolody et al. 2008) have been adopted here to maintain comparability. The structural assumptions tested included the spatial disaggregation, biological and movement parameters, and statistical assumptions. This defined a factorial grid design where each assumed parameter was a factor having two or more alternative values (Table 3). The various combinations of parameter assumptions produced 256 model runs for a given spatial option.

1. Spatial disaggregation

Models were developed for three alternative spatial options for all or subsets of the 4 areas:

Option	Areas
2ar	1, 2
4ar	3, 4
1_4ar	1 to 4

2. Biological parameters

For two of the spatial options (2ar, 4ar), models were fitted assuming a range of biological parameter values (Table 3). The basis for the parameter specifications is described by Kolody et al. (2008), and an outline follows. The parameter assumptions and abbreviations used by Kolody et al. (2008) have also been used here to facilitate ready comparisons between the parallel assessments.

A Beverton-Holt stock-recruitment relationship with assumed steepness options of 0.65 and 0.90 was used (h65, h90 respectively, Table 3). Given that a meta-analysis of stock-recruitment relationships indicated 0.75 to be a plausible steepness value (Myers et al. 1999), the options used represent a relatively wide range.

Eight options for combined growth, natural mortality and maturity schedules were considered (Figure 6, Table 3). These options account for differences in estimated growth and maturity schedules between laboratories (CSIRO, NMFS), and for alternative relationships with respect to natural mortality and maturity. As such, there were four options each for either fast (GHMLS, GHML, GHMHS, GHMH) or slow (GAMLS, GAML, GAMHS, GAMH) growth and maturity.

3. Movement parameters

Kolody & Davies (2008) discuss recent satellite and conventional tagging observations and they infer maximum diffusion rates between the areas specified in the model domain. The two assumed rates for quarterly diffusion were 0.05 and 0.1 (D05, D10 respectively, Table 3).

4. Statistical assumptions

The relative weightings of the two data types to which the model was fitted, i.e., CPUE and catch-at-length, were specified in the likelihood function by the observation error assumed. High assumed error assigns low relative weight. Alternative options explored assumed relative weightings for these data types given differences in the reliability and conflicts apparent between these data.

Observation error estimates for the standardised CPUE were not available for all fisheries, and a broad assumption was made that the c.v. for the AU and NZ fisheries was 0.1 over all years, and for the DP and DW fisheries it was 0.25 over all years. This reflects the view that the catch and effort reporting systems for the Australian and New Zealand fisheries are better administered. An alternative option considered the reverse relative weighting. These CPUE relative weighting options were denoted UAJ and UJA respectively (Table 3).

The catch-at-size data was down-weighted by a factor of either 20 or 5 by multiplicatively down-scaling the sample sizes (ES20 or ES5 respectively, Table 3).

5. Fishery definitions

Either the Minimal and Extended fleet options for the defined fisheries (Table 1) were assumed (min and ext respectively, Table 3). This was to account for possible differences between the DW and PN selectivity estimates.

Parameters estimated

The assumptions made for the spatial disaggregation affect the function of certain parameters. Implicitly, the longitudinal block structure of the areas requires that parameters other than movement coefficients proxy for seasonal swordfish movement in the North-South direction. Consequently, these within-area dynamics were described by spatio-temporal differences in fleet-specific catchability and selectivity parameters. Consequently, these parameters were estimated specific to each fleet-zone-quarter.

i) Selectivity-at-length
Size-based functions were estimated and were specific in respect of fleet nationality, zone and season, but were assumed constant over all areas. The respective fleet

nationalities depended upon the fishery definition factor assumed for the uncertainty grid: three for iFishery = min, DP (Japanese, distant water fleets, and PINs), AU (Australia), and NZ (New Zealand), and four for iFishery = ext, DW (Japanese, distant water fleets), PN (Pacific Island Nations, PINs), AU (Australia), and NZ (New Zealand). Subscripting fleet-specific selectivities in respect of season and zone accounted for seasonal and latitudinal patterns in catch size compositions.

A double normal function was assumed that permits either a "domed" or non-decreasing function, with the following normally distributed prior:

	a_1	s_L	s_R
μ	100.0	20.0	1000.0
cv	0.5	0.5	1.0

where a_1 is the length at maximum selectivity, s_L and s_R is the distance (in units of length) below and above a_1 (respectively) at which selectivity reduces by 50%.

ii) Mean recruitment (R_0)
This is the mean annual number of swordfish recruiting at age 0 year to the population, and that produces the virgin population size under zero fishing mortality. Recruitment was assumed to be distributed uniformly among the model areas. A uniform-log prior distribution was assumed with upper and lower bounds of 1.0E+07 and 75 000, respectively.

iii) Annual year class strengths (YCS, 1970 – 2007)
The Haist parameterisation (Bull et al. 2005) was assumed for annual recruitment variability, which rescales all year class strengths to constrain the mean YCS index to a value of 1.0. The prior distribution assumed was uniform with lower and upper bounds of 0.01 and 20.0. Insufficient observations were available before 1970 to enable the estimation of YCS for the period 1951 to 1969. Constant mean recruitment (R_0) was assumed for these years.

vii) Catchability
Catchability coefficients (q) were calculated analytically as nuisance parameters for each fishery for which an observed CPUE time series was available. Uniform-log prior distributions were assumed with upper and lower bounds of 1.0 and 1.0E-08, respectively. Catchabilities were specific to fleet, area-zone, and quarter. This was based on the assumption that the observed variations in catch rates amongst seasons, areas and zones reflect latitudinal and seasonal migrations. The fleet specific catchabilities were not scaled according to the relative effective area associated with the observed CPUE in each because the areas were approximately of similar dimensions (Kolody et al. 2008).

Estimation procedure

For each "cell" of the uncertainty grid, the mode of the Bayesian posterior distribution (MPD) was obtained to give point estimates of parameters from a maximum likelihood fit to the observations. It was assumed the CPUE random variable was log-normally distributed. The objective function term for the catch-at-size data was the robustified multivariate normal likelihood (Fournier et al. 1990, adapted by Bull et al. 2005), in which the variances are obtained by assuming binomial variability for each length class with a small additional constant. The individual likelihood terms making up the total objective function and the selected formulations are described by Bull et al. (2005).

Bayesian mean estimates were not calculated from an MCMC posterior distribution for logistical reasons.

Quality of fit criteria

The approach described by Kolody et al. (2006, 2008) was adopted for identifying individual plausible models from the 256 estimated over the uncertainty grid. This included three criteria for assessing the quality of the model fit to the observations. For evaluating the quality of the model fit to the CPUE observations, independent of the assumed variance, the Root Mean Squared Error (RMSE) for fishery *f* was :

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

Similarly, for evaluating the quality of the model fit to the catch-at-size observations, independent of the assumed sample sizes, the Effective Sample Size (McAllister & Ianelli 1997) was used:

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

Where $p_{t,l}$ and $o_{t,l}$ are the predicted and observed proportions caught-at-length in year t, respectively. The ESS for fishery f is:

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

To consider the general quality of fit, the minimum, maximum and average RMSE and ESS over all fisheries was calculated.

The mean size bias was calculated from the model and observed estimates of catch-at-size, over all years for each fishery.

Derived quantities

Model estimates were derived for quantities used to assess stock size and its relative status in terms of current total and spawning stock biomass, (TSB and SSB respectively). These quantities were also derived for the corresponding model run under zero assumed fishing mortality (TSBNF and SSBNF).

Model predictions of TSB and SSB were obtained from 10-year projections assuming constant annual catch equal to the levels reported in each fishery in 2007 and constant annual recruitment equal to R_0.

A list of the derived quantities for the particular years selected follows.

- TSB(2007)/TSB(1997)
- SSB(2007)/SSB(1997)
- TSB(2007) / TSBNF(2007)
- SSB(2007) / SSBNF(2007)
- TSB(2007)/TSB(MSY)
- SSB(2007)/SSB(MSY)
- F(2007)/F(MSY)
- TSB(2012) / TSB(2007)
- SSB(2012) / SSB(2007)
- TSB(2012) / TSB(1997)
- SSB(2012) / SSB(1997)
- TSB(2012) / TSB(MSY)
- TSB(2017) / TSB(MSY)

To employ the CASAL modelling framework for swordfish, it was necessary to specify all aspects of the population state and associated variables as being weightless because all catch and observations were expressed in terms of numbers of fish. Hence, estimates of TSB and SSB at the population levels that can support maximum sustainable yield (MSY) could not be expressed in terms of biomass, but rather in terms of the abundance in numbers of fish. All derived quantities relating to MSY were therefore in terms of numbers of fish, i.e. current and future stock status.

Results

<u>Spatial option 2ar</u>

Uncertainty grid – model quality of fit

Although the quality of model fit was similar among models, a large number of implausibly high estimates of absolute abundance were obtained, and many of these were associated with a higher mean and maximum RMSE (i.e., a worse fit to CPUE), and a larger ESS (i.e., a better fit to catch-at-size), (Figure 7). However, in respect of the AU and NZ observations, a similar quality of fit was obtained irrespective of the estimates of absolute abundance. No relationship between absolute abundance and quality of fit was clear, although generally more instances of implausibly high abundance were estimated with a poor quality fit to the AUS catch-at-size observations (Figure 8).

Varying the relative weight of CPUE and catch-at-size had a predictable effect on the quality of fit, with higher ESS under higher relative weight for catch-at-size data, a bimodal density function for the ESS of NZ catch-at-size data, and a modest effect on that of the AU catch-at-size data (Figure 9). However, this effect was not related to implausibly high abundance estimates, (Figure 10). The density functions for other uncertainty factors showed no clear bimodality, apart from a modest increase in RMSE for the AU and NZ CPUE given lower relative weight. Hence, there was no clear basis for specifying model implausibility in relation to the effects of particular uncertainty factors on the quality of fit.

More than 50% of the models produced implausibly high estimates of absolute abundance, 1 order of magnitude higher than a large mode of 103 model runs having absolute abundances of less than 2 million fish (Figure 10). Given the data conflicts apparent, and the probable local minima associated with particular grid options, that may produce extremely high model abundance estimates, these were regarded as being implausible for a number of reasons. In all these instances R_0 was close to, or at, the upper bounds. The abundance estimates correspond to a TSB of around 2 million t, which is of similar magnitude yellowfin tuna over a comparable spatial domain that supports an associated fishery of 400 000 t annually (Langley et al. 2007). Estimated fishing impacts for these models were around 1-2%, and this contrasts strongly with independent studies suggesting local depletion in the Australian fishery. Consequently, the subset of 103 models was retained as being plausible, and for which the quality of fit criteria were examined in relation to the uncertainty factors.

The quality of fit to Australian and New Zealand CPUE indices was reduced for model options assuming slow growth and reduced relative weight (Figures 11 and 12). As can be expected the quality of fit to Australian and New Zealand catch-at-size time series was sensitive to the assumed relative weight of these data, and was also reduced for model options assuming slow growth (Figures 13 and 14). In terms of mean size bias, the quality of fit to the Australian catch-at-size was worse for models assuming slow growth and lower relative weight for Australian and New Zealand CPUE (Figure 15), while the quality of fit to the New Zealand catch-at-size was worse for model assuming higher relative weight for Australian and New Zealand CPUE (Figure 16). This result indicates a level of conflict between these data sets, although this should be interpreted cautiously given the extremely low magnitude of the bias being measured (less than 4 cm).

Of the uncertainty factors tested, the options for steepness of 0.65, slow growth rates, and low relative weight for CPUE from DP and DW fisheries were less prevalent in the 103 model subset, indicating that these factors were more associated with less plausible models (Figure 17). The low prevalence of the uncertainty factor for steepness of 0.65 consequently resulted in low variability for both quality of fit criteria and derived quantities (Figures 11 to 16 and Figures 18 to 31, respectively).

Uncertainty grid – derived quantities

The estimated derived quantities: TSB(2007)/TSB(1997), SSB(2007)/SSB(1997), TSB(2007)/TSBNF(2007), and SSB(2007)/SSBNF(2007) were less variable for models assuming the option for high relative weight of CPUE for the AU and NZ fisheries, (Figures 18 to 21). The median value for these indicators in terms of TSB was similar over all the uncertainty factors, while those in terms of SSB were sensitive to the uncertainty factor options assumed for: relative weight of the CPUE data, and the fishery definitions. TSB(2007)/TSB(1997) was around 62%, SSB(2007)/SSB(1997) is lower at around 42% (Table 4).

TSB(2007)/TSB(MSY) estimates were less variable for models assuming the option for high relative weight of CPUE for the AU and NZ fisheries, (Figure 22). The median values were sensitive to the uncertainty factor options assumed for steepness, growth and relative weight for the CPUE time series, such that models assuming low steepness, slow growth and high relative weight for DP/DW CPUE produced lower estimates of population abundance relative to TSB(MSY) (Figure 22). This was also evident for SSB(2007)/SSB(MSY) in respect of steepness and the relative weight for DP/DW CPUE (Figure 23). This pattern was reflected in the F(2007)/F(MSY) estimates being higher for models assuming these uncertainty factor options (Figure 24).

The derived quantities in respect of 5-year predicted abundance (TSB(2012)/TSB(1997), SSB(2012)/SSB(2007), TSB(2012)/TSB(2007), SSB(2012)/SSB(1997)) were lower and less variable for models assuming uncertainty factor options for low steepness and slow growth, and were higher and less variable for models assuming high relative weight for AU and NZ CPUE data (Figures 25 to 28).

This pattern was similar for derived quantities in respect of predicted abundance relative to MSY-related measures (TSB(2012)/TSB(MSY), TSB(2017)/TSB(MSY)) that were lower for models assuming uncertainty factor options for low steepness and slow growth, and were higher and less variable for models assuming high relative weight for AU and NZ CPUE data (Figures 29 and 30).

The median current biomass relative to the estimated unexploited level for TSB and SSB, was 39% and 20% respectively (Table 4). The median current abundance (in numbers) relative to the MSY-related reference point level for TSB and SSB was 126% and 242% respectively, although these quantities were highly variable. The median current exploitation rate relative to the MSY-related reference point level was 60%, and this quantity was also highly variable.

The variability in the two estimated derived quantities of stock status: TSB(2007)/TSB(MSY), and F(2007)/F(MSY), was high, ranging from 44% to 180%, and from 26% to 282%, respectively. This variability spanned the range of stock status, although a high proportion (around 80%) of the models indicated the stock is not in an overfished state and there is currently no overfishing (Figure 31). There was no clear indication that this variability was strongly related to the quality of fit, in that models at the extremes of the distribution exhibited similar quality of fit criteria to models having values close to the median. Therefore, the variability appeared not to relate to structural uncertainty affecting the goodness of fit, and in the 103 model subset, a similar quality of fit was possible from models having divergent structural assumptions.

Model estimates

Year class strengths

Recent year classes show a declining trend through the period 1998 to 2002, with a recent increase to 2006 (Figure 32). The index for 2007 is highly uncertain and this may be attributed to the paucity of catch-at-size observations for this year class.

Population biomass
A clear decline in total stock biomass to 2005 is estimated with a recent increase to 2007 (Figure 33). This increase most likely reflects the recent increase in recruitments to above average levels (Figure 32). The total stock biomass density plots demonstrate the high uncertainty in model estimates of absolute abundance with a long tail for high biomass estimates relative to the median values of around 36,000 t in 1952 to around 13,000 t in 2005, with a subsequent increase and stabilising at around just 18,000 t in model projections. A similar trend is predicted for spawning stock biomass albeit at the substantially lower level of abundance (Figure 33).

Example model fit
The quality of fit to the observations is presented for an example model that is close to the median with the range of the 103 model subset. This illustrates the relatively good level of fit to the CPUE and catch-at-size observations possible within the subset. The assumed values for the uncertainty factors for this example model were: steepness = 0.9; growth-mortality-maturity option = GHML; relative catch-at-size downweighting = 20; relative CPUE weighting = UAJ; migration = D05; and, fishery specification = minimal.

The fit to the DP, AU and NZ fishery CPUE time series is presented in Figures 34 to 41. Although the fit to the observations appear generally good, with model indices reflecting observed trends in relative abundance, for most time series (besides the AU fishery), a pattern in the residuals indicates a deviation from the assumptions of normality (see Q-Qnorm plots in Figures 34 to 41). Despite reflecting the pattern in observed relative abundance, observed CPUE for the DP fishery in area 1, zone C, were consistently over-estimated in recent years, whereas the fit for the AU fishery was good (Figure 37). This illustrates the data conflicts among the fleet-specific CPUE time series. The fit to the components of the NZ and AU catch-at-size time series presented in Figures 42 and 43, show examples of the generally good fit to observations from these fisheries, and reflect the shift in the mode of the AU observations to a smaller mean size.

Seasonal and zone-specific selectivity at length for the AU, NZ and DP fisheries example model are presented in Figures 44 and 45, illustrating clear seasonality in selectivity patterns in the AU and NZ fisheries. However, many of the DP fleet estimates were spiked and seemingly implausible.

Model function minimisation problems

A test to the initial parameter values assumed when fitting the model, indicated clear sensitivity to these values, i.e., function minimisation problems caused by an inability of the estimation procedure to find global optimum solutions.

The test used two example models from the 103 model subset, having similar assumptions regarding the uncertainty factors. The parameter estimates from the first fit for each model were switched between models and used as the initial start parameters for a second model fit. The effect of this test relative to model population abundance for the first and second estimations was compared (Figure 46). There was a clear difference between the estimates such that the second estimates were more similar to the first estimates obtained for the other model. This indicates a significant source of uncertainty contributing to the variability in the estimated derived quantities, and hence, stock status.

Spatial option 4ar

256 models were estimated over the uncertainty factors included in the grid design, however, more for than 90% of these the mean recruitment parameter estimates were at the upper bound of the prior distribution, and many other parameters were similarly bounded. In particular, most selectivity estimates were implausible having spiked functions. There was no indication that a global solution was obtained for total population abundance in areas 3 and 4 (Figure 47).

Spatial option 1_4ar

A large number of the parameters were estimated at or close to the bounds of the prior distributions, with implausibly high abundance estimates. There was clear conflict between the CPUE data that was not able to be resolved under the assumptions made in the model. This is illustrated for an example model where a relatively good fit obtained to the CPUE time series in Areas 1 and 2, results in a poor fit to the series in areas 3 and 4 (Figure 48). Subsequent attempts failed to obtain improved fits to the observations or plausible estimates. Estimating structural uncertainty using the uncertainty grid design was not attempted for this spatial option.

Discussion

The specific recommendations from the 2006 CASAL stock assessment of south-west Pacific swordfish (Davies et al. 2006) were addressed in that a wide range of sources of uncertainty were explored, and attempts were made to include the south-central Pacific Ocean within the model domain. A total of 526 models were estimated (all converged successfully) over a wide range of structural and statistical assumptions. This represents a considerable improvement in the consideration of uncertainty relative to the 2006 CASAL assessment.

Similar estimates for certain derived quantities were obtained from the CASAL model for the 2ar spatial option with those of the parallel MFCL assessment. The median relative change in absolute biomass since 1997 was 0.62 and 0.69 for the CASAL and MFCL models respectively, and predicted relative change to 2012 was 1.185 and 1.19 respectively. However, all derived quantities from the CASAL model were more variable, and most were less optimistic. The CASAL model results for the 2ar spatial option revealed two primary sources for this variability: structural uncertainty and function minimisation problems.

Structural uncertainty

Assumptions made for many of the parameters and statistical specifications included in the uncertainty factors determined the variability in the derived quantities. The uncertainty grid design revealed data conflict and a quality of fit dependant upon assumed parameters. Generally, the quality of fit to the CPUE was worse for models assuming slow growth and high relative weight for the catch-at-size data. Conflict was evident between the CPUE data for the DP and AU fisheries in area 1, zone C, indicated by the quality of fit being sensitive to the assumed relative weight in respect of each fishery. Both the AU and NZ CPUE indices show recent increases that are higher compared to the DP fisheries. This conflict determined variability in the derived quantity for the relative change in biomass, which was less variable for models assuming the option for high relative weight of CPUE for the AU and NZ fisheries. These indices suggest a “recovery” in relative abundance from a sustained decline that most likely constrains parameter estimates. This also determined the variability in the derived quantities for stock status, in that hey were less variable for models assuming the option for high relative weight of CPUE for the AU and NZ fisheries. Certain assumptions produced a more pessimistic stock status, viz. assuming low steepness, slow growth, and high relative weight for DP/DW CPUE produced lower estimates of population abundance relative to TSB_{MSY}, and higher F_{curr} relative to F_{MSY}. As such, models with lower productivity (growth) achieved a higher quality of fit to the DP and DW CPUE, and predicted a more pessimistic estimate of stock status compared to models assuming higher productivity with a higher quality of fit to the AU and NZ CPUE. This pattern was reflected in the derived quantities from model projections under these uncertainty factor assumptions that produced a pessimistic or optimistic outlook respectively.

Function minimisation problems

A significant problem for the CASAL assessment was model function minimisation problems in that there was a clear indication for the lack of convergence on a global minimum. This was revealed by a simple test using two similarly-specified models that produce widely divergent absolute abundance estimates. Switching the fitted parameters to be used as the start values between the models for a repeat of the model fit produced estimates divergent relative to the initial model fit and more similar to the other model. This suggests that model solutions from local minima of the objective function were highly probable for CASAL model estimates. This would add to the variability of derived quantities making it difficult to determine the underlying distribution of model derived quantities. The median values of these quantities may not necessarily be associated with solutions from global minima of the objective function. This limits the depth of interpretation possible from the CASAL results, particularly for absolute abundance estimates that exhibited sensitivity to this source of uncertainty.

Possible causes of this source of uncertainty relate to the model estimation procedure, the number of parameters estimated, and, data conflicts. CASAL model parameters were estimated simultaneously in a single procedure to optimise the objective function. This differs from the MFCL approach that utilises a phased estimation procedure, with successive optimisations for selected parameter estimations in each. This reduces the potential for producing solutions associated with local minima.

A large number of selectivity and catchability parameters were estimated to account for temporal and latitudinal variability in CPUE and catch-at-size. However, scant data were available for some fisheries, areas, zones and seasons (especially DP, DW and PN), making parameter estimation difficult. Although seasonality in selectivity patterns in the AU and NZ fisheries was found, the DP selectivities appeared implausible in many instances (spiked). This suggests the model may have been over-parameterised relative to the information available, but seasonality in the catchability coefficients did appear plausible. In combination with the observed conflicts between data types, this would create potential for a range of parameters producing a similar objective function value, and most likely local minima. This feature highlights the dilemma of either assuming more model processes and estimating fewer parameters, e.g., movement associated with spawning and foraging site fidelity as in the 2006 CASAL assessment, or, making fewer assumptions and estimating more parameters. This represents the trade-off often necessary between accounting for process or observation error in designing model structure and formulating statistical assumptions.

Stock status

The swordfish population biomass in areas 1 and 2 is predicted to have declined dramatically since 1952 to a relatively low level in 2005 (around 35% of the 1952 level) with a subsequent increase due to above average recent YCS since 2004-05. Model projections show that, with a return to average recruitments, the increase in stock size asymptotes at around 45% of the 1952 level.

In light of the discussion above regarding model uncertainty, estimates of relative change in biomass are likely to be the most reliable from the CASAL assessment. The derived quantities suggest a substantial decline (38%) in total biomass over the past 10 years. Over the next 5 years total biomass is predicted to increase by 18.5% but will remain below, at 76% of, the historical (1997) level.

The estimates of stock status relative to B_{MSY} and F_{MSY} are uncertain, with high variability caused by structural uncertainty and function minimisation problems. In addition, these derived quantities must be interpreted in relation to their calculation in terms of numbers of fish rather than biomass. As discussed below, the effect of this is to decrease the ratio estimate relative to the corresponding ratio in terms of biomass, i.e., stock status appears more pessimistic. The median for the derived quantity TSB(2007)/TSB(MSY) is lower than the MFCL estimate (1.259 versus 1.57) and this most likely reflects this effect.

Differences with respect to the Multifan-CL parallel assessment

There are four differences between the MFCL and CASAL assessments that make direct comparisons between the results difficult:

1) the CPUE time series included in the model fit,
2) the fishery selectivities estimated,
3) CASAL function minimisation problems, and,
4) the formulation of MSY-related derived quantities.

For the MFCL assessment, Kolody et al. (2008) assumed the DP and DW CPUE time series in zone 2 of areas 1 and 2 were indicative of relative abundance, and excluded the series in zones 1 and 3 from the model fit. All indices from the DP and DW CPUE were included in the CASAL model estimation. This difference in the statistical assumptions between the two assessment models was examined for a small subset of CASAL models. The effect was primarily to reduce variability in the derived quantities.

The rationale behind the estimation of seasonal, fishery-, and zone-specific selectivities was to proxy for temporal and latitudinal movement processes. For the minimal and extended fleet options 20 and 28 selectivity functions were estimated, respectively. This contrasts with the four selectivities estimated for the MFCL model (that assumes the minimal fleet option). Consequently, and in combination with the fishery- and season-specific catchability coefficients estimated, the CASAL model had more "freedom" to achieve a good quality of fit to seasonality in CPUE and catch-at-size. However, catch-at-size sample sizes were relatively low for the DP, DW and PN fleets, and, for which, often implausible (spiked) selectivity functions were estimated, indicating insufficient information in these data. The large number of parameters required for estimating selectivities for these fleets was most likely in excess of what the available data could support, i.e. the CASAL model may have been over-parameterised.

The discussion above identified the problem of function minimisation problems for the CASAL assessment model. Model estimates are unlikely to be associated with solutions from global minima of the objective function, and comparisons between the medians of the CASAL model derived quantities with those of the MFCL model are unlikely to be informative, particularly for quantities sensitive to this problem, e.g., absolute abundance. Given that all of the 103 subset of models estimated a similar biomass trend, quantities such as relative change in absolute abundance were less uncertain. Whereas, estimates of stock status relative to MSY-related reference points were.

There are fundamental differences in the MSY-related reference points derived from the CASAL and MFCL models. For the CASAL model, these quantities were expressed in terms of abundance in numbers of fish, rather than typically biomass (as used for the MFCL estimates). Necessarily, the CASAL model was structured as weightless, i.e., the population state and all derived quantities were frequencies of fish and not biomass. This was required for accommodating the frequency-type input data and no implicit biomass conversions are currently active in the CASAL framework in this context.

The effect of this difference between the CASAL and MFCL derived quantities for stock status relative to MSY levels may be considered in terms of the ratios of current estimates of abundance relative to MSY-related performance indicators expressed as either biomass or numbers of fish. This ratio alters with the change in mean fish weight at various population sizes. Mean weight declined concurrent with the population decline from the unexploited equilibrium level in 1952, and consequently a higher number of individuals currently make up an equivalent biomass relative to that in 1952. For the example model, current abundance relative to that in 1952 was 82% and 47% in terms of numbers and biomass, respectively. This reflects the effect of removing older and larger fish from the population. It follows that the ratio abundance at the MSY level (B_{MSY}) relative to B_0 will be substantially higher in terms of numbers than for biomass. Consequently, when current abundance is higher than B_{MSY}, as is the case of median values in this assessment, the ratio of current abundance to B_{MSY} will be lower in terms of numbers than in terms of biomass. As such, the MSY-related derived quantities for the CASAL model will be more pessimistic compared to those reported for the parallel MFCL assessment.

This difference is less pronounced for spawning stock reference points, where the decline mean weight of the spawning population concurrent with that of the population was minimal. However, for the example model presented, the spawning stock makes up a small fraction of the total population numbers at B_{MSY}, around 5%, compared to 36% at B_0. This substantial difference makes it difficult to infer general comparisons with spawning stock status for derived quantities expressed in terms of biomass. Therefore, no direct comparisons with those quantities from the MFCL assessment were attempted.

The weightless aspect of the CASAL model structure has implications for the specification of the spawner-stock-recruitment relationship (SRR) such that the spawning stock is expressed in numbers rather than weight. This is not biologically realistic since individual fish weight is cubically related to length, and fecundity is more related to fish weight than to adult numbers. Given the discussion above regarding relativity between spawning stock numbers and biomass, the SRR would most likely have predicted less recruitment compensation than had spawning stock been expressed in terms of biomass, i.e., predicted lower productivity at low stock size. Given the model estimates of spawning stock decline to around 20% of unfished levels, models assuming low steepness (h65) would have predicted lower productivity than that for a SRR expressed in terms of spawning stock biomass. This mis-specification of the SRR in the CASAL model most likely contributed to this steepness option being less prevalent in the models considered plausible (the 103 model subset).

In summary, the derived quantities are uncertain because of problems with achieving optimum solutions for the parameters. However, the quantities for relative change in biomass are likely to be more reliable and are indeed consistent with those presented for the parallel MFCL assessment. The CASAL model derived quantities for stock status are expressed in terms of numbers and are consequently more pessimistic than if expressed in terms of biomass. In light of the function minimisation problems in the CASAL model, it is suggested that the derived quantities for stock status from the parallel assessment using MFCL are more reliable than those presented here.

Areas 3 and 4

Among the 256 combinations of uncertainty factors tested for the 4ar spatial option, none produced mean recruitment parameter estimates that were below the upper bound, or were plausible model estimates. Over the range of models tested, there was no indication of convergence towards an estimated distribution for absolute abundance. This suggests that overall there was a lack of information available for estimating population abundance and this result supports the following view expressed at the Open Workshop for the 2008 swordfish assessment in regards stock structure.

"The Workshop noted that there was no strong evidence supporting the assumption of a single stock across the southern Pacific, but noted that there is some evidence based on the distribution of catch, CPUE, genetics and spawning locations suggesting the possibility of two separate stocks:

- Whilst swordfish are mainly caught within the central temperate zones in Areas 1 and 2, the catch of swordfish in Areas 3 and 4 is mainly within the northern equatorial zone.
- The spatial distribution of Japanese CPUE suggests a possible discontinuity between south-western and north-eastern equatorial areas of the southern WCPO (though the central zones of Areas 3 and 4 do indicate high Japanese and Spanish CPUE).
- The generally decreasing trends in nominal CPUE for the major fleets catching swordfish in Areas 1 and 2 (Japan, Australia and New Zealand) are dissimilar with the generally increasing nominal CPUE trends of the major fleets catching swordfish in the northern zones of Areas 3 and 4 (Japan, Korea and Taiwan)."

Anon (2008).

The paucity of catch-at-size data from areas 3 and 4 combined with an uncertain CPUE time series exhibiting a steadily increasing trend, from the northern zone only, offers limited information for estimating the relatively large number of parameters. The CASAL model function minimisation problems experienced for the 2ar spatial option models, would most likely have added to difficulties in obtaining model convergence.

The model estimation problems for areas 3 and 4 would have contributed to the lack of success in obtaining a plausible model for the 1_4ar spatial option. Under the single stock assumptions including common YCS among all areas and uniform distribution of recruitment among areas, the model was not able to resolve the conflict between the CPUE indices in areas 1 and 2 versus areas 3 and 4. Given this result, and the high uncertainty in model estimates, it was concluded that a single stock assumption was not reasonable for a population model including areas 1 to 4 combined. Consequently, the status of the swordfish stocks in the south-central Pacific Ocean could not be estimated from this assessment.

References

Alvarado Bremer, J.R. Hinton, M.G. and Greig, T.W. 2006. Evidence of the spatial genetic heterogeneity in Pacific swordfish revealed by the analysis of LDH-A sequences. *Bull. Mar. Sci. 79(3)*: 493-503.

Anon. (2008). Report of the Southern WCPO Swordfish Assessment Workshop. April 16−18, 2008 Secretariat for the Pacific Community, Noumea, New Caledonia. Information Paper SA-IP-1 to WCPFC SC4, held 11-22 August 2008, Port Moresby PNG.

Bull, B.; Francis, R.I.C.C.; Dunn, A.; McKenzie, A.; Gilbert, D.J.; Smith, M.H. (2005). CASAL (C++ algorithmic stock assessment laboratory): CASAL User Manual v2.07-2005/08/21. NIWA Technical Report 127. 272 p.

Campbell, R. (2002). Sequential changes in swordfish catch rates off eastern Australia and possible implication for the spatial distribution of the local swordfish population. Standing Committee on Tuna and Billfish. SCTB15 Working Paper BBRG-9, 13 p.

Campbel1, R., Unwin, M., Davies, N., Miyabe, N. (2008). Swordfish CPUE Trends across the Southern WCPO. Information Paper SA-IP-4 to WCPFC SC4, held 11-22 August 2008, Port Moresby PNG. 33 p.

Campbell, R. (2008). Data summary pertaining to the catch of swordfish by longline fleets operating in the southern WCPO. Information Paper SA-IP-3 to WCPFC SC4, held 11-22 August 2008, Port Moresby PNG.

Campbell, R. and Davies, N. 2008. South Pacific swordfish fisheries and observers data summary: catch, size and sex. Working paper for the swordfish stock assessment workshop, 16-18 April 2008. Secretariat for the Pacific Community, Noumea, New Caledonia.

Chow, S.; Okamoto, H.; Uozumi, Y.; Takeuchi, Y. (1997). Genetic stock structure of the swordfish (*Xiphias gladius*) inferred by PCR-RFLP analysis of the mitochondrial DNA control region. Marine Biology 127: 359-367

Davies, N., Campbell, R., Kolody, D. (2006). CASAL stock assessment for south-west Pacific broadbill swordfish 1952-2004. Methods Specialist Working Group paper presented at the 2nd meeting of the Scientific Committee of the Western and Central Pacific Fisheries Commission, 7-16 August 2006. WCPFC-SC2 ME-WP-4.

Deriso, R.B.; Quinn II, T.J.; Neal, P.R. (1985). Catch-age analysis with auxiliary information. Canadian Journal of Fisheries and Aquatic Sciences 42: 815–824.

Fournier, D.; Archibald, C.P. (1982). A general theory for analyzing catch at age data. Canadian Journal of Fisheries and Aquatic Sciences 39: 1195–1207.

Fournier, D.A.; Sibert, J.R.; Majkowski, J.; Hampton, J. (1990). MULTIFAN: a likelihood-based method for estimating growth parameters and age composition from multiple length frequency data sets illustrated using data for southern bluefin tuna. *Canadian Journal of Fisheries and Aquatic Sciences 47*: 301–317.

Kleiber, P., Hampton, J. and D. Fournier. 2003. MULTIFAN-CL User's Guide. http://www.multifancl.org/usersguide.pdf.

Kolody, D.; Campbell, R.; Davies, N. (2006). Multifan-CL Stock Assessment for South-West Pacific Broadbill Swordfish 1952-2004 Methods Specialist Working Group paper presented at the 2nd meeting of the Scientific Committee of the Western and Central Pacific Fisheries Commission, 7-16 August 2006. WCPFC-SC2 ME-WP-3.

Kolody,D. and Davies, N. Spatial structure in South Pacific Swordfish Stocks and Assessment Models. Information Paper SA-IP-2 to WCPFC SC4, held 11-22 August 2008, Port Moresby PNG.

Kolody, D., Campbell, R., Davies, N. (2008). A Multifan-CL Stock Assessment of South-Western-Central Pacific Swordfish 1952-2007. Working Paper SA-WP-6 to WCPFC SC4, held 11-22 August 2008, Port Moresby PNG. 89 p.

Langley, A.; Hampton, J.; Kleiber, P.; Hoyle, S. (2007). Stock assessment of yellowfin tuna in the western and central Pacific Ocean, including an analysis of management options. Working Paper SA-WP-1 to WCPFC SC3, held 13-24 August 2007, Honolulu, Hawai'i. 116 p.

McAllister, M.K. and Ianelli, J.N. 1997. Bayesian stock assessment using catch-age data and the sampling-importance resampling algorithm. *Can. J. Fish. Aquat. Sci. 54*: 284-300

Methot, R.D. (1990). Synthesis model: an adaptable framework for analysis of diverse stock assessment data. International North Pacific Fisheries Commission Bulletin 50: 259–275.

Murray, T.; Griggs, L. (2006). Factors affecting swordfish (Xiphias gladius) catch rate in the New Zealand tuna longline fishery. New Zealand Fisheries Assessment Report (in prep.)

Myers, R.A., Bowen, K.G. and N.J. Barrowman. 1999. Maximum reproductive rate of fish at low population sizes. *Can. J. Fish. Aquat. Sci. 56*: 2404-2419.

Reeb, C.A.; Arcangeli, L.; Block, B. (2000). Structure and migration corridors in Pacific Ocean populations of the swordfish, *Xiphias gladius*, as inferred through analysis of mitochondrial DNA. Working paper BBRG-13 presented at the 13th meeting of the Standing Committee on Tuna and Billfish, held 5-12 July 2000, Noumea, New Caledonia.

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Figure 35: Swordfish CPUE for the DP fishery in area 1, zone 2 (spatial option 2ar) showing observed (-o-) and fitted (-e-) values (top panel) for an example model, with diagnostic plots of the normalised residuals (bottom two panels).

Figure 36: Swordfish CPUE for the DP fishery in area 1, zone 3 (spatial option 2ar) showing observed (-o-) and fitted (-e-) values (top panel) for an example model, with diagnostic plots of the normalised residuals (bottom two panels).

Figure 37: Swordfish CPUE for the AU fishery in area 1, zone 2 (spatial option 2ar) showing observed (-o-) and fitted (-e-) values (top panel) for an example model, with diagnostic plots of the normalised residuals (bottom two panels).

Figure 38: Swordfish CPUE for the DP fishery in area 2, zone 1 (spatial option 2ar) showing observed (-o-) and fitted (-e-) values (top panel) for an example model, with diagnostic plots of the normalised residuals (bottom two panels).

Figure 39: Swordfish CPUE for the DP fishery in area 2, zone 2 (spatial option 2ar) showing observed (-o-) and fitted (-e-) values (top panel) for an example model, with diagnostic plots of the normalised residuals (bottom two panels).

Figure 40: Swordfish CPUE for the DP fishery in area 2, zone 3 (spatial option 2ar) showing observed (-o-) and fitted (-e-) values (top panel) for an example model, with diagnostic plots of the normalised residuals (bottom two panels).

Figure 41: Swordfish CPUE for the NZ fishery in area 2, zone 2 (spatial option 2ar) showing observed (-o-) and fitted (-e-) values (top panel) for an example model, with diagnostic plots of the normalised residuals (bottom two panels).

Figure 42: Swordfish catch-at-length time series for the NZ fishery, area 2 zone 2 in the second quarter showing observed (-o-) and fitted (-e-) values for the example model (spatial option 2ar).

Table 1: Fisheries definitions for the regional stock assessment model for south-west-central Pacific swordfish for the Minimal and Extended fleet options in respect of area, zone and nationality.

Minimal fleet

Fishery label	**Area**	**Zone**	**Description**	**Selectivity ogive**
1	1	N	Japanese + distant water fleets + PIN	DP
2	1	C	Japanese + distant water fleets + PIN	DP
3	1	S	Japanese + distant water fleets + PIN	DP
4	1	N + C + S	Australian domestic (includes 2C)	AU
5	2	N	Japanese + distant water fleets + PIN	DP
6	2	C	Japanese + distant water fleets + PIN	DP
7	2	S	Japanese + distant water fleets + PIN (includes Japanese charter in 2S and 2C)	DP
8	2	C	NZ domestic (includes 2S and 1C)	NZ
9	3	N	Japanese + distant water fleets + PIN	DP
10	3	C + S	Japanese + distant water fleets + PIN	DP
11	4	N	Japanese + distant water fleets + PIN	DP
12	4	C + S	Japanese + distant water fleets + PIN	DP

Extended fleet

Fishery label	**Area**	**Zone**	**Description**	**Selectivity ogive**
1	1	N	Japanese + distant water fleets	DW
2	1	C	Japanese + distant water fleets	DW
3	1	S	Japanese + distant water fleets	DW
4	1	N + C + S	Australian domestic	AU
5	1	N + C	Pacific Island fleets	PN
6	2	N	Japanese + distant water fleets	DW
7	2	C	Japanese + distant water fleets	DW
8	2	S	Japanese + distant water fleets	DW
9	2	N	Pacific Island fleets	PN
10	2	C	Pacific Island fleets	PN
11	2	C	NZ domestic	NZ
12	3	N	Japanese + distant water fleets	DW
13	3	C + S	Japanese + distant water fleets	DW
14	3	N	Pacific Island fleets	PN
15	3	C + S	Pacific Island fleets	PN
16	4	N	Japanese + distant water fleets	DW
17	4	C + S	Japanese + distant water fleets (includes Pacific Island fleets in 4C)	DW
18	4	N	Pacific Island fleets	PN

Table 2: Start and end years for the CPUE and catch-at-size time series, with catch-at-size sample sizes for the fisheries (Minimal and Extended fleet options) defined for the regional stock assessment models for south-west-central Pacific swordfish.

Minimal fleet

Fishery label	Area	Zone	Selectivity ogive	CPUE standardised	Catch-at-size: years	Catch-at-size: sample size
1	1	N	DP	1971_1 – 2006_4	1971-2006	4167
2	1	C	DP	1971_1 – 2006_4	1971-2006	7478
3	1	S	DP	1971_1 – 2006_4	1990-2001	280
4	1	N + C + S	AU	1997_3 – 2007_4	1997-2007	244775
5	2	N	DP	1971_1 – 2006_4	1971-2006	1828
6	2	C	DP	1971_1 – 2006_4	1971-2006	7646
7	2	S	DP	1971_1 – 2006_4	1988-2003	641
8	2	C	NZ	1998_1 – 2007_3	1992-2007	15449
9	3	N	DP	1971_1 – 2006_4	1996-2006	904
10	3	C + S	DP	-	1995-2006	6384
11	4	N	DP	1971_1 – 2006_4	1996-2006	541
12	4	C + S	DP	-	1999-2006	901

Extended fleet

Fishery label	Area	Zone	Selectivity ogive	CPUE standardised	Catch-at-size: years	Catch-at-size: sample size
1	1	N	DW	1971_1 – 2006_4	1971-2006	2240
2	1	C	DW	1971_1 – 2006_4	1971-2004	7091
3	1	S	DW	1971_1 – 2006_4	1990-2001	280
4	1	N + C + S	AU	1997_3 – 2007_4	1997-2007	244775
5	1	N + C	PN	-	1993-2006	2314
6	2	N	DW	1971_1 – 2006_4	1971- 2006	290
7	2	C	DW	1971_1 – 2006_4	1971-2004	6397
8	2	S	DW	1971_1 – 2006_4	1988-2003	641
9	2	N	PN	-	1993-2006	1538
10	2	C	PN	-	1993-2006	1249
11	2	C	NZ	1998_1 – 2007_3	1992-2007	15449
12	3	N	DW	1971_1 – 2006_4	2002-2004	521
13	3	C + S	DW	-	2004	5692
14	3	N	PN	-	1996-2006	383
15	3	C + S	PN	-	1995-2006	692
16	4	N	DW	1971_1 – 2006_4	1999-2005	407
17	4	C + S	DW	-	1999—2006	901
18	4	N	PN	-	1996-2006	134

Table 3: Alternative parameter options assumed for a factorial grid design used for estimating structural uncertainty, with the abbreviation used for denoting the 256 model runs for a given spatial option.

Parameter	**Label**	**Assumed values**	**Abbreviation**
Steepness (Beverton-Holt)	iSteep	0.65, 0.9	h65, h90
Growth, M, Maturity	iGrow	NMFS-lowPref-L+M NMFS-lowPref-L NMFS-hiPref-L+M NMFS-hiPref-L CSIRO-lowPref-L+M CSIRO-lowPref-L CSIRO-hiPref-L+M CSIRO-hiPref-L	GHMLS GHML GHMHS GHMH GAMLS GAML GAMHS GAMH
Catch-at-size weight	iCatchWei	20, 5	ES20, ES05
CPUE fleet weight	iCPUE	$cv_{AU,NZ} = 0.1$; $cv_{DP,DW} = 0.25$	UAJ, UJA
Migration rates (qtrly)	iMigrate	0.05, 0.1	D05, D10
Fishery definitions	iFishery	Minimal fleet, Extended fleet	min, ext

Table 4: Median, minimum and maximum values for the estimated performance indicators (see text) for the set of 103 models.

	Median	**Min**	**Max**
TSB(2007)/TSB(1997)	0.620	0.414	0.780
SSB(2007)/SSB(1997)	0.418	0.216	0.633
TSB(2007)/TSBNF(2007)	0.390	0.134	0.655
SSB(2007)/SSBNF(2007)	0.204	0.050	0.543
TSB(2007)/TSB(MSY)	1.259	0.440	1.801
SSB(2007)/SSB(MSY)	2.422	0.492	5.052
F(2007)/F(MSY)	0.604	0.262	2.821
TSB(2012)/TSB(2007)	1.185	0.137	1.763
SSB(2012)/SSB(2007)	1.758	0.128	4.158
TSB(2012)/TSB(1997)	0.756	0.062	1.029
SSB(2012)/SSB(1997)	0.713	0.028	1.171
TSB(2012)/TSB(MSY)	1.196	0.056	1.740
TSB(2017)/TSB(MSY)	1.201	0.000	1.702

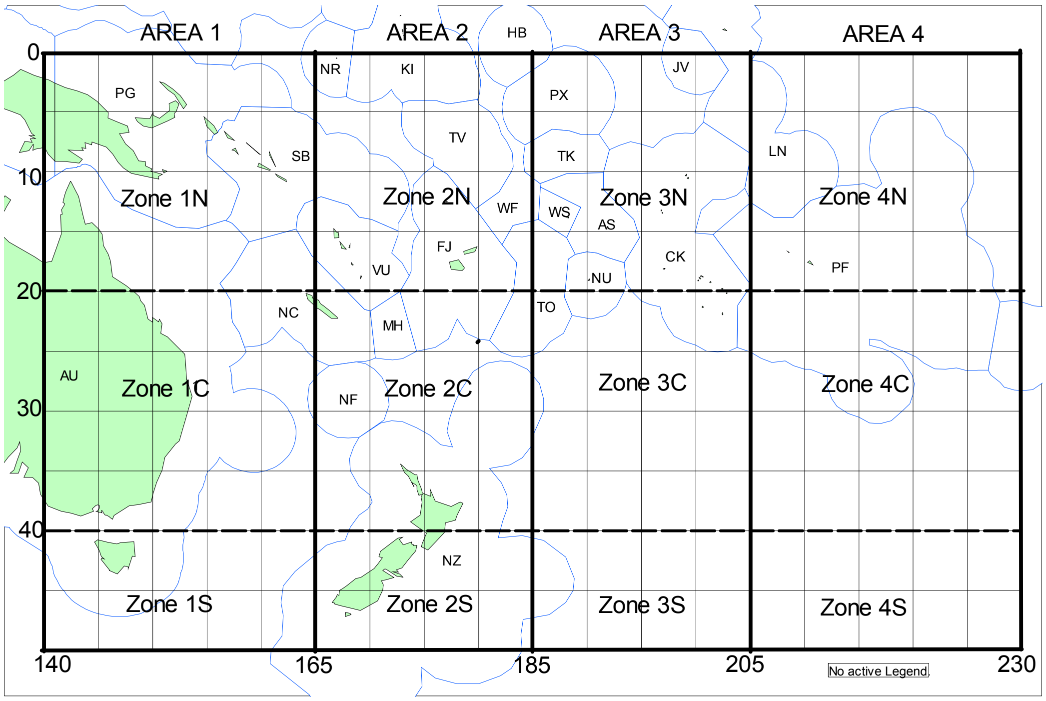


Figure 1: Spatial disaggregation of the south-west Pacific region assumed for the swordfish regional stock assessment model, by areas, and fishery definition zones.

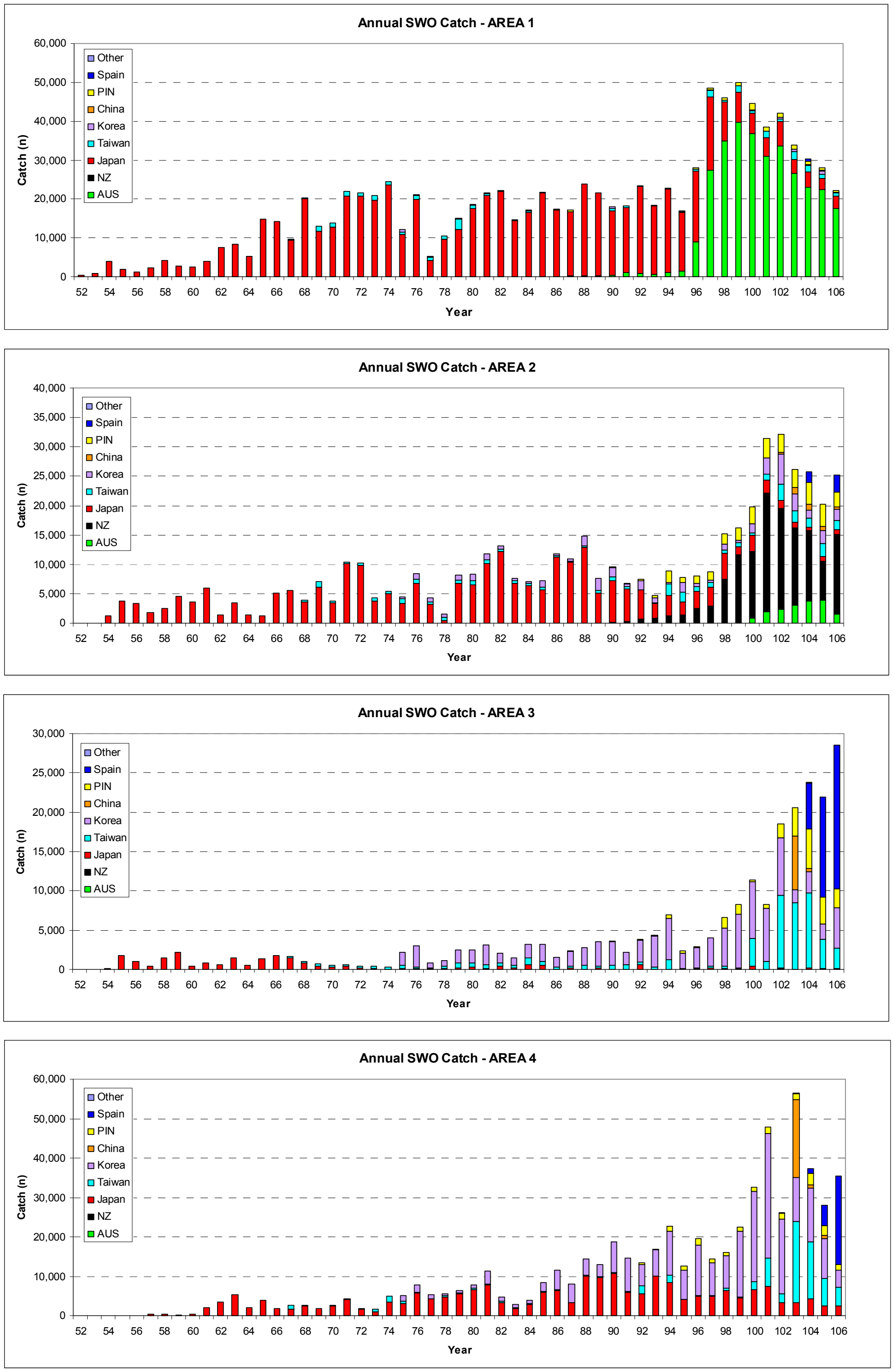


Figure 2: Annual longline swordfish catch (number of fish) for the major longline fleets within the four assessment regions of the southern WCPO.

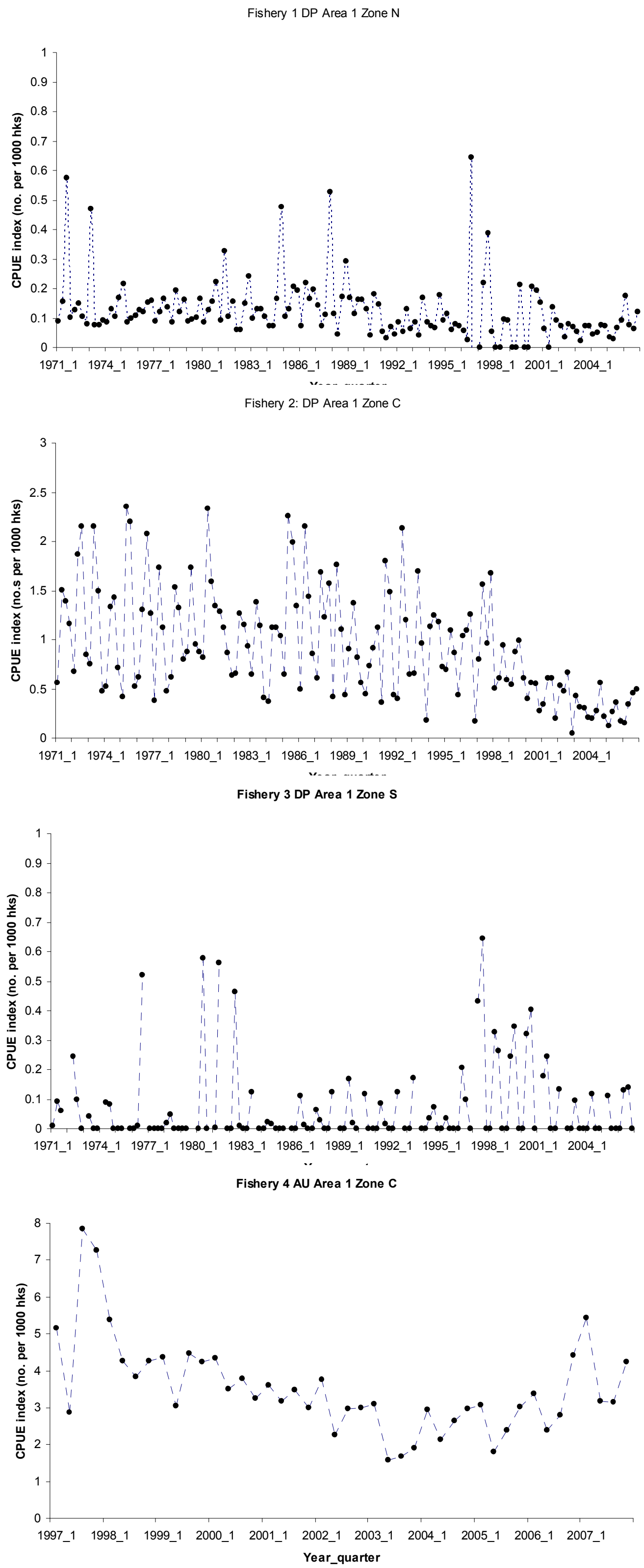


Figure 3: Standardised CPUE indices for the AU and DP time series in model area 1 by the defined fishery zones (North, Central and South) for the minimal fleet option.

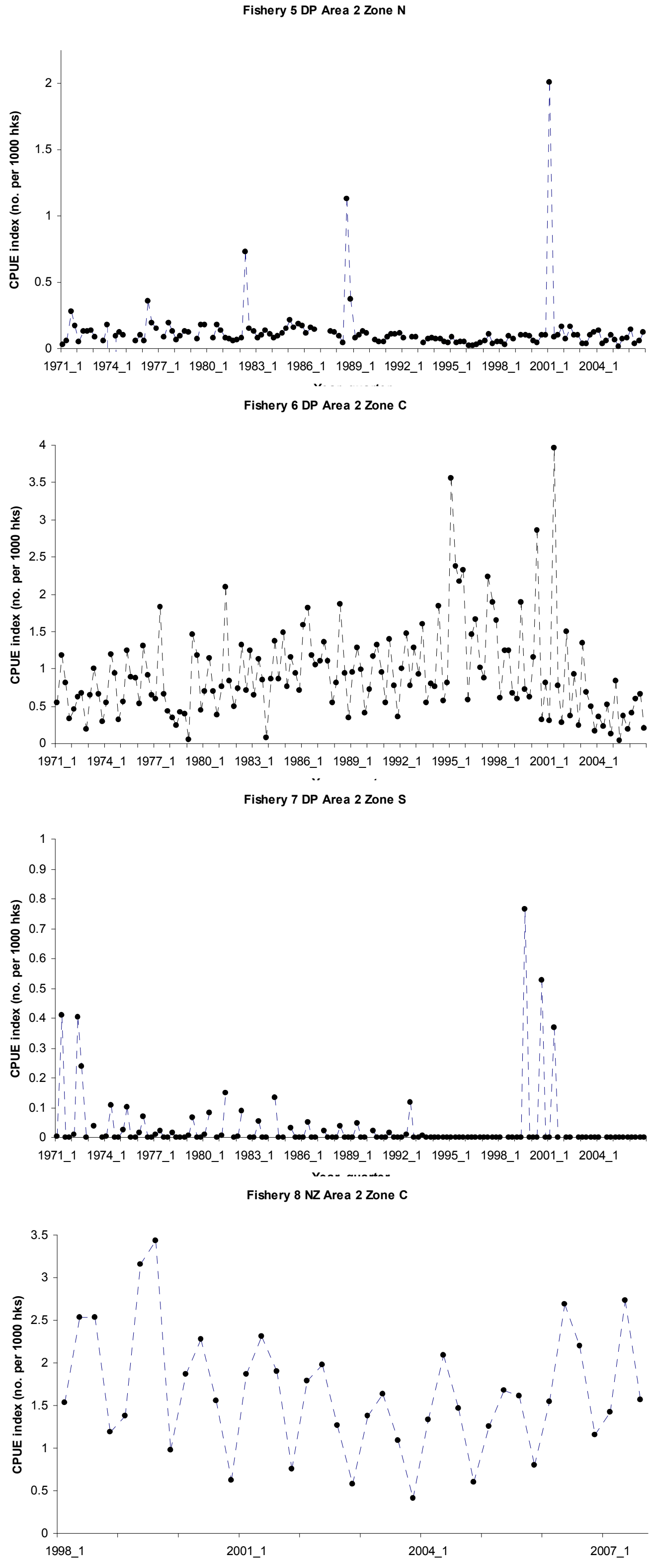
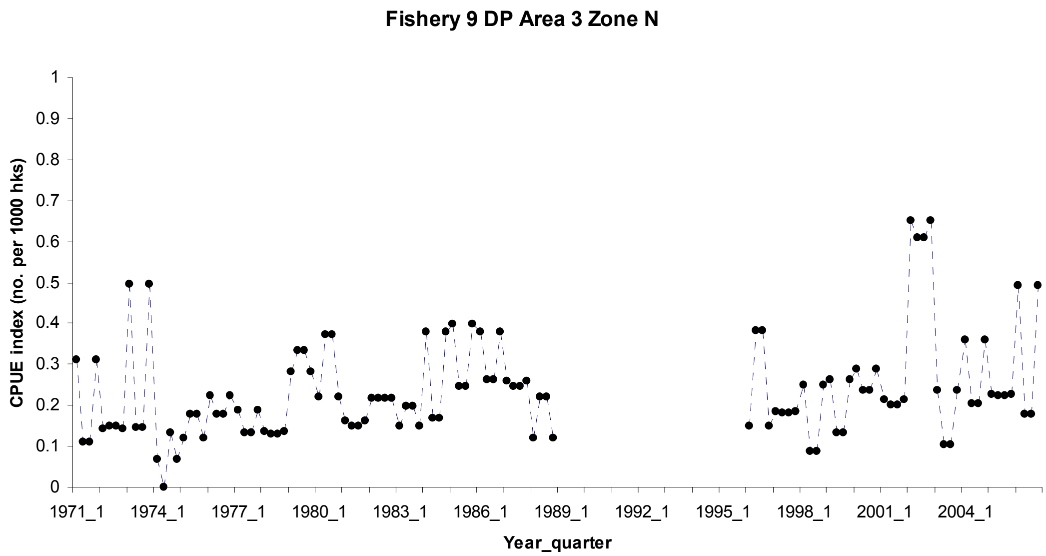


Figure 4: Standardised CPUE indices for the NZ and DP time series in model area 2 by the defined fishery zones (North, Central and South).



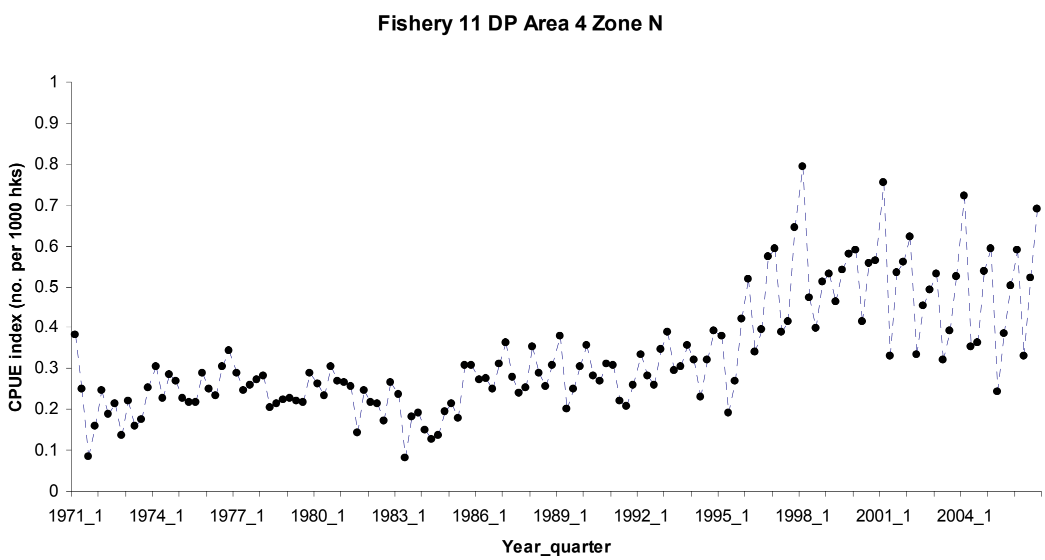


Figure 5: Standardised CPUE indices for the DP time series in model areas 3 and 4 (top and bottom panels, respectively) for the defined fishery zone North.

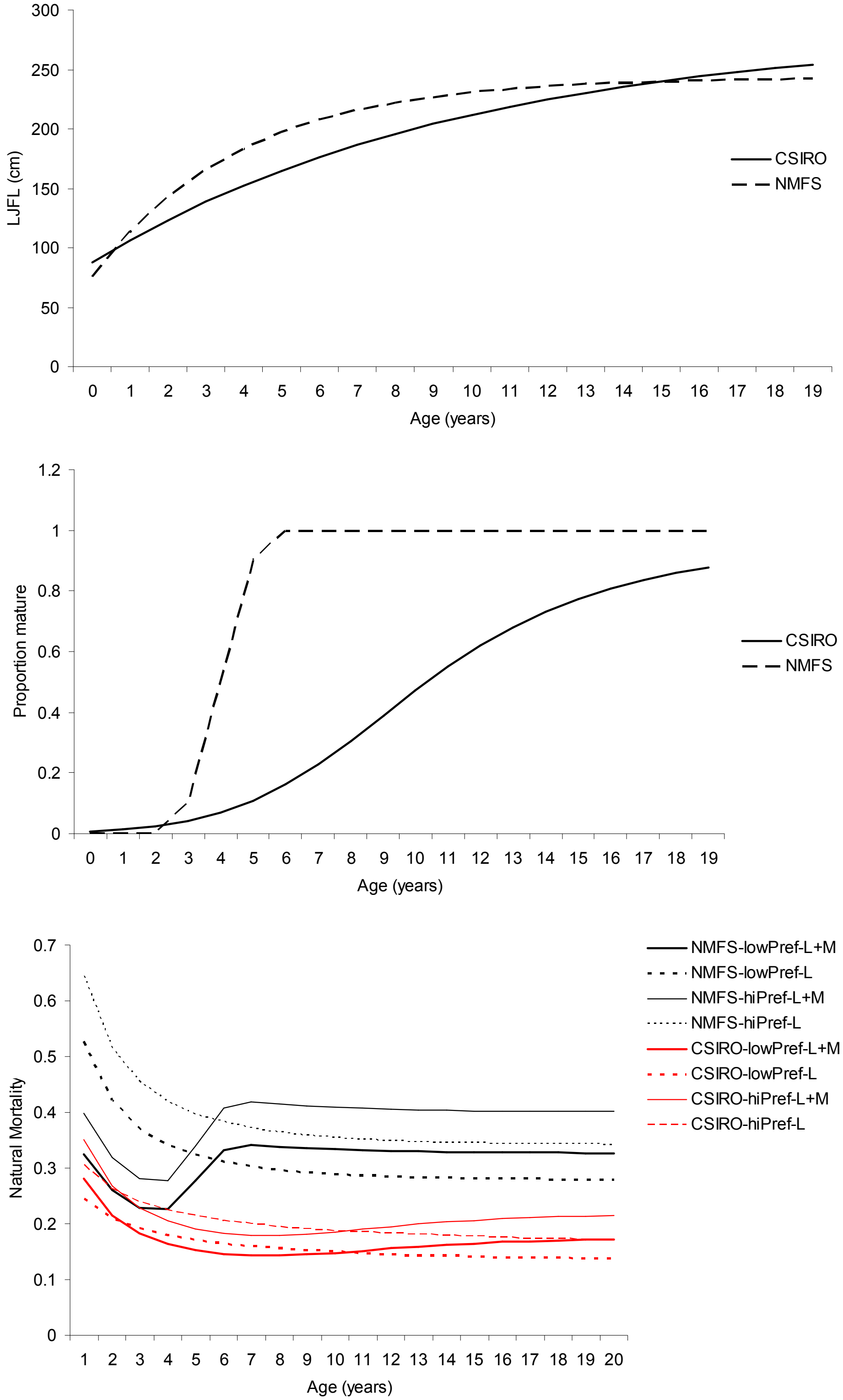


Figure 6: Age-specific functions for growth, maturity, and natural mortality (top, middle and bottom panels respectively) assumed for the factorial grid design.

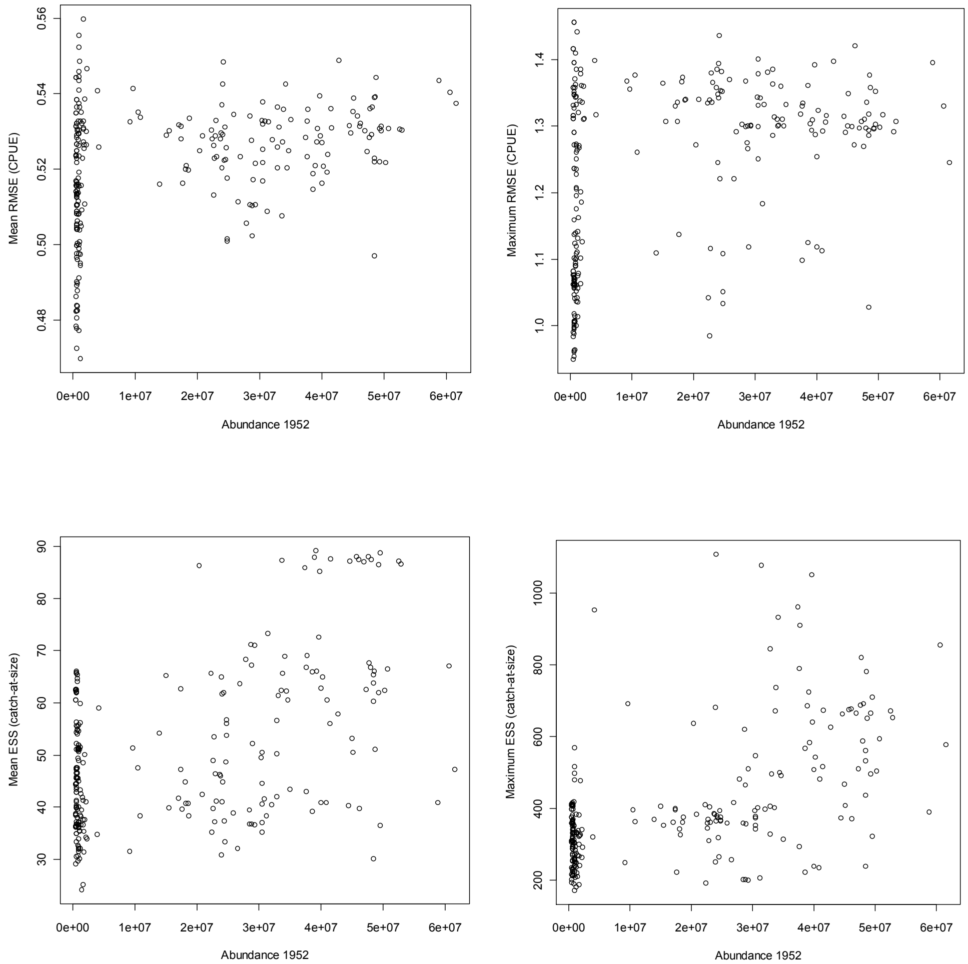


Figure 7: Scatterplots of the mean and maximum RMSE of the model fit to the CPUE time series, and the mean and maximum ESS from the model fit to the catch-at-size time series, with respect to model estimates of absolute abundance (numbers of fish) in 1952.

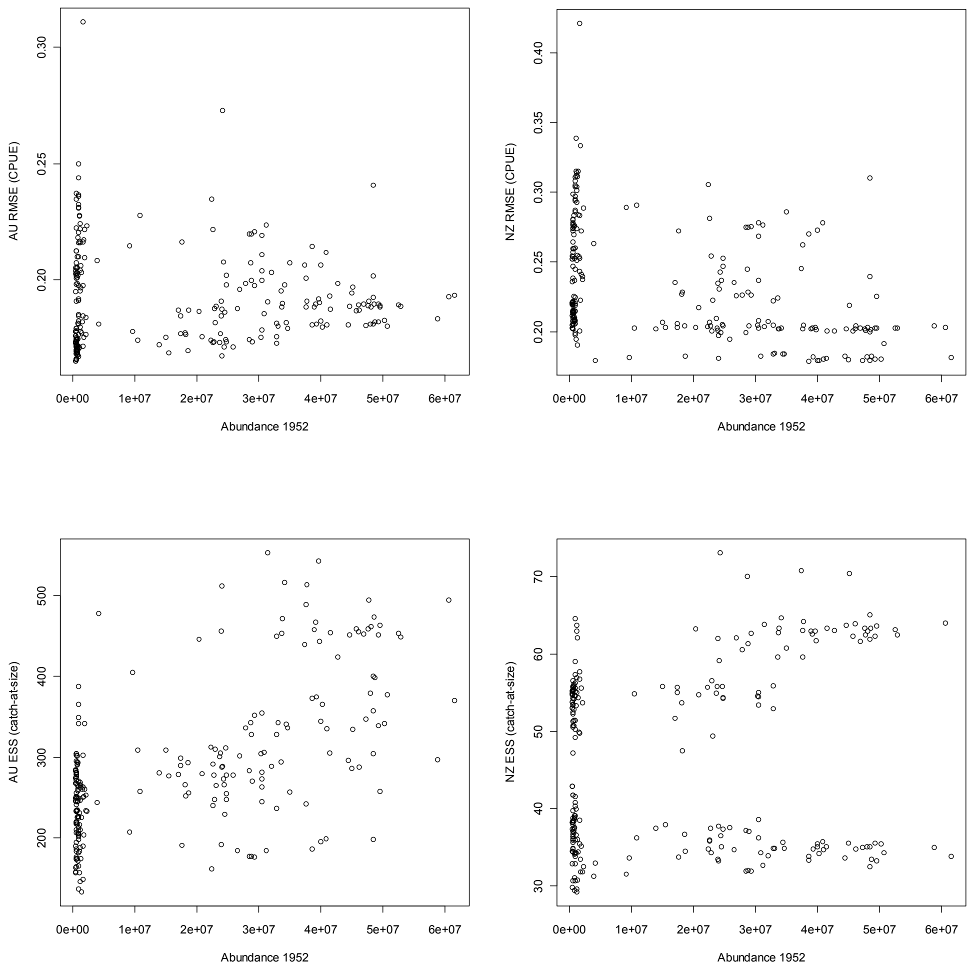


Figure 8: Scatterplots of the RMSE of the fit to the Australian (AU RMSE) and New Zealand (NZ RMSE) CPUE data, and the ESS from the fit to the Australian (AU ESS) and New Zealand (NZ ESS) catch-at-size data, with respect to model estimates of absolute abundance (numbers of fish) in 1952.

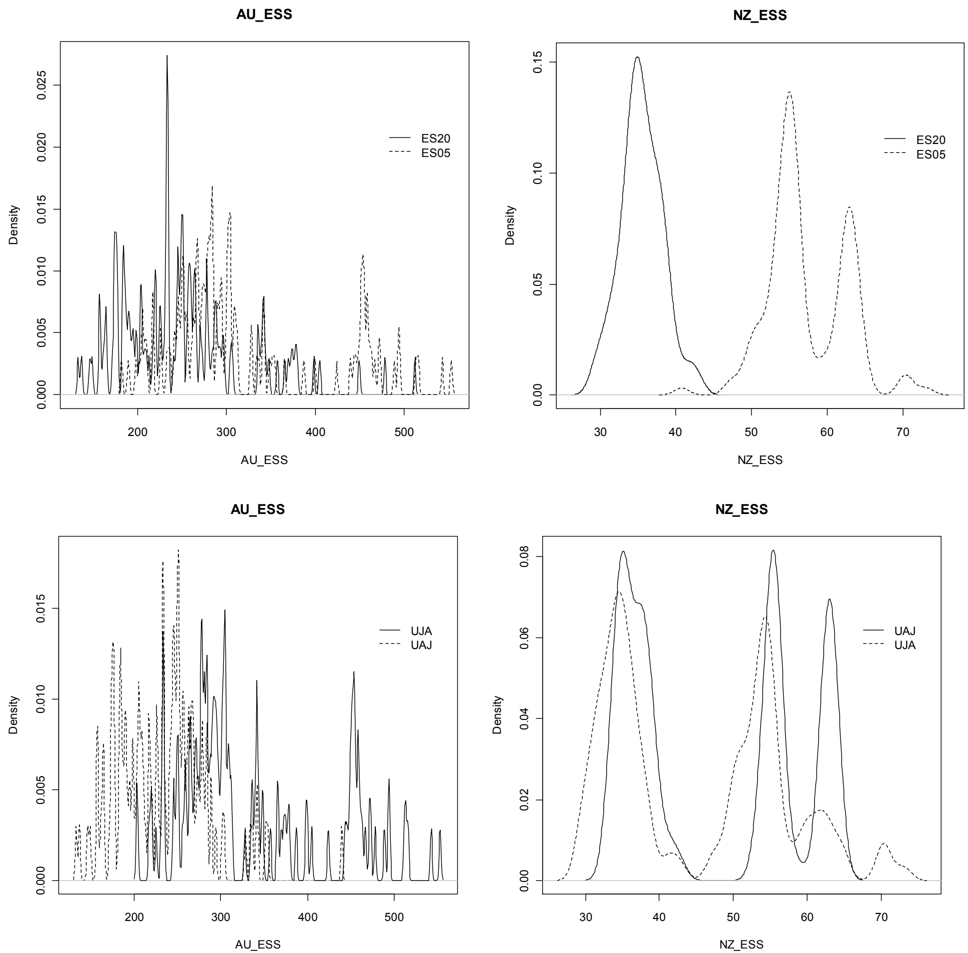
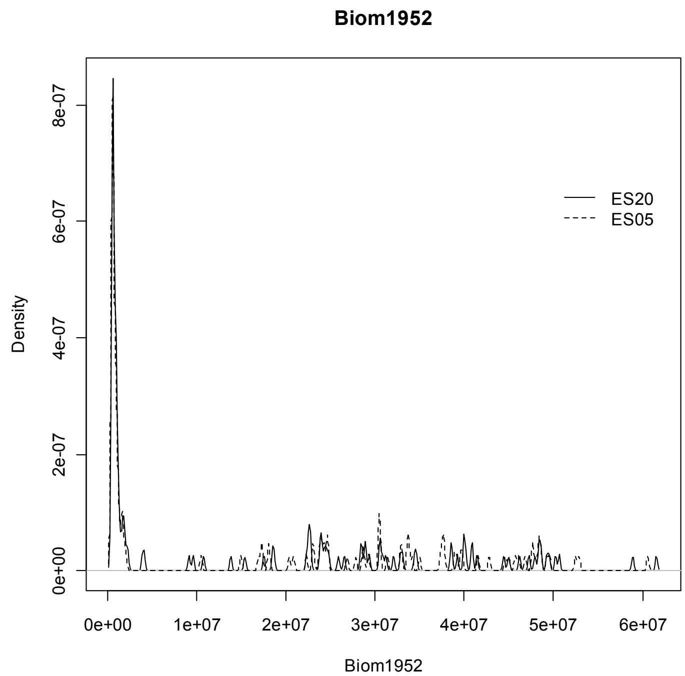


Figure 9: Density functions of the effective sample size from the fit to Australian (AU_ESS) and New Zealand (NZ_ESS) catch-at-size data with respect to the uncertainty factors: relative weight of catch-at-size (ES20, ES05) and CPUE (UJA, UAJ) data.



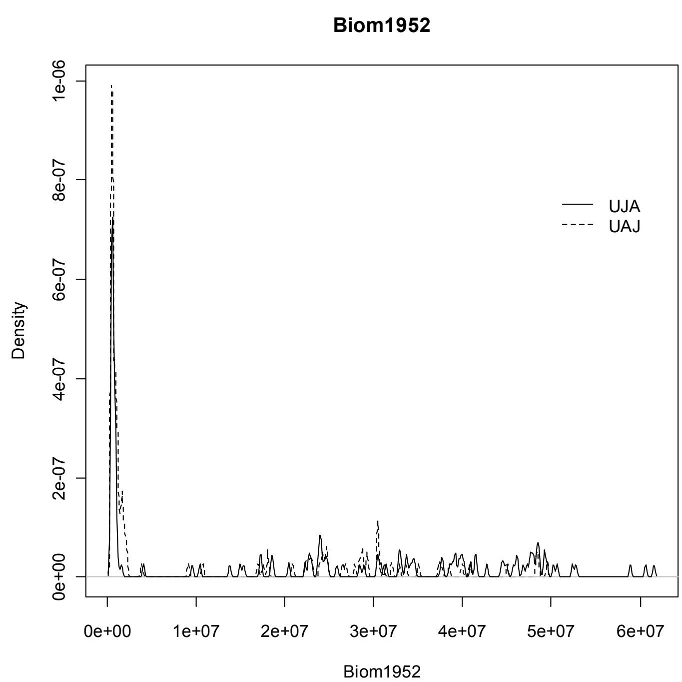


Figure 10: Density functions of model absolute abundance estimates (numbers of fish) in 1952 with respect to the uncertainty factors: relative weight of catch-at-size (ES20, ES05) and CPUE (UJA, UAJ) data.

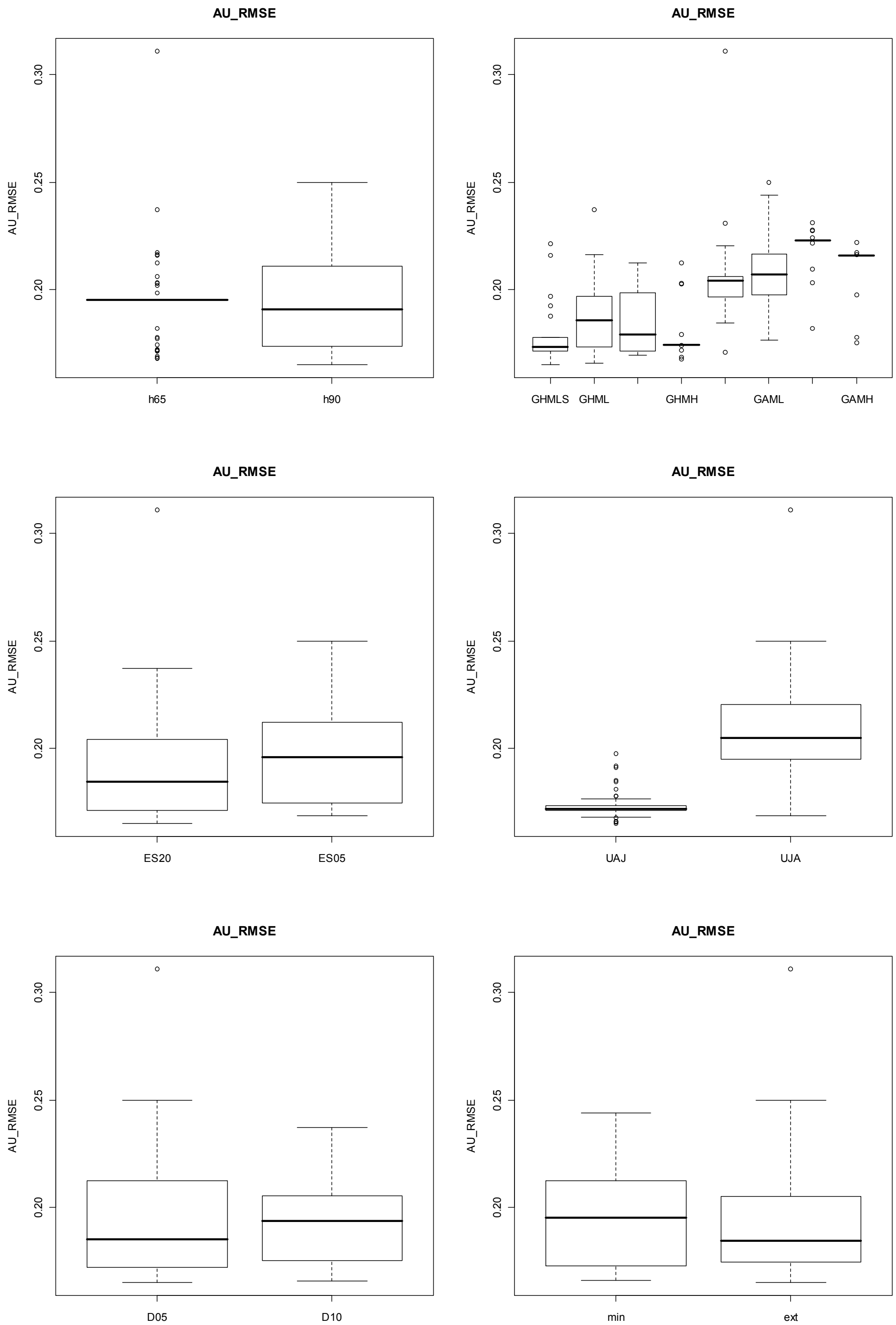


Figure 11: Boxplots of the RMSE of the fit to Australian CPUE indices with respect to model uncertainty factors.

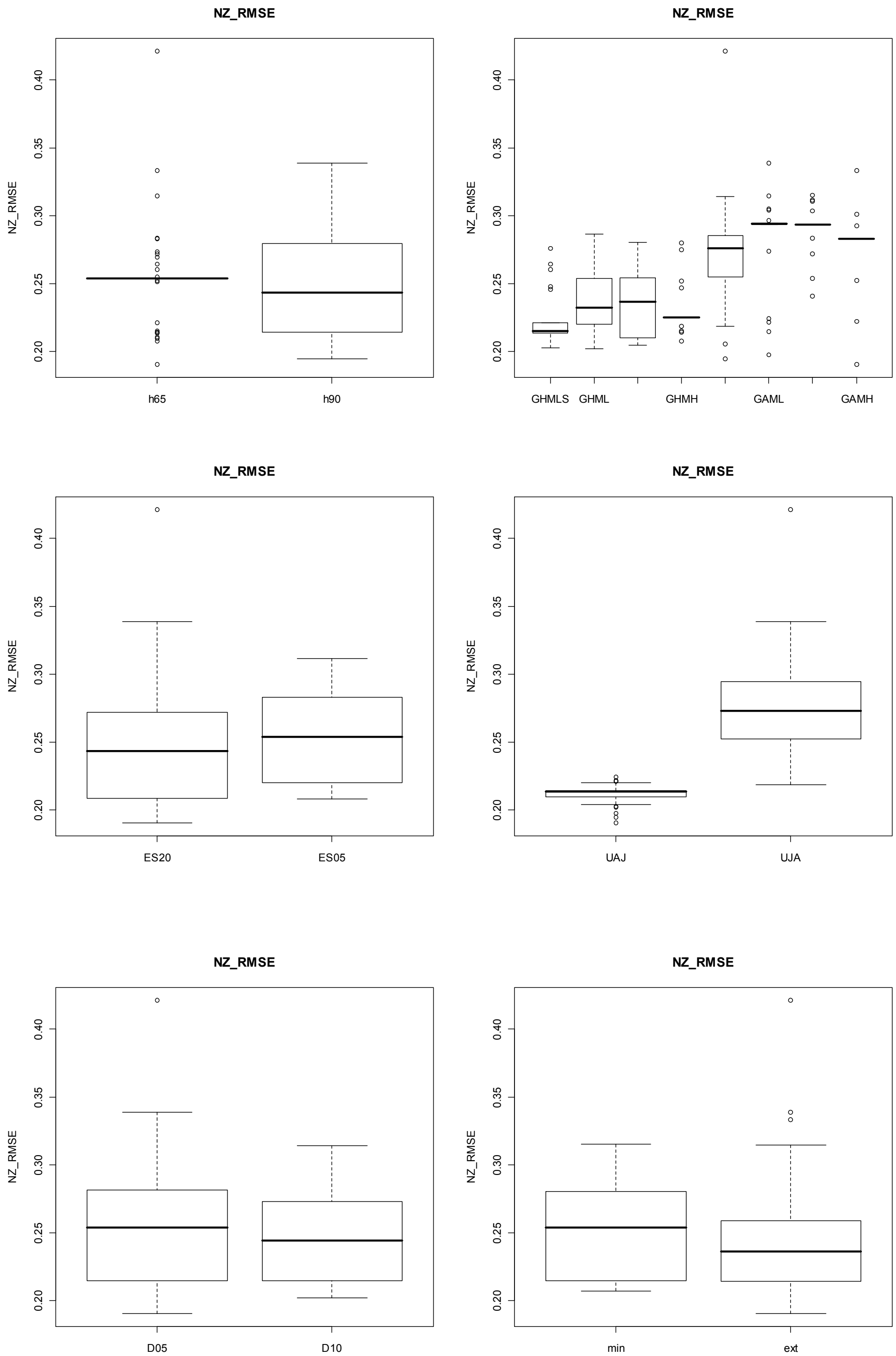


Figure 12: Boxplots of the RMSE of the fit to New Zealand CPUE indices with respect to model uncertainty factors.

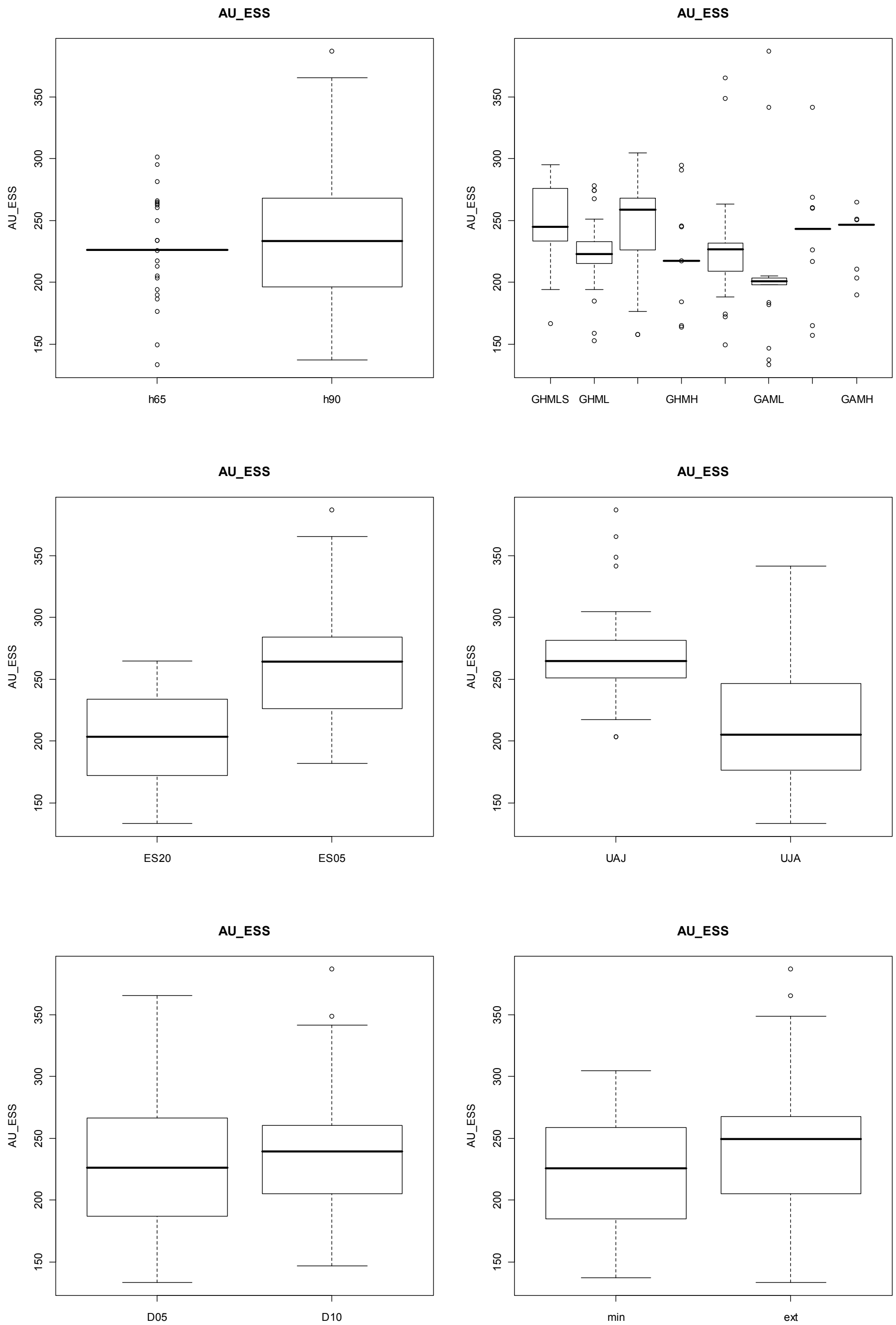


Figure 13: Boxplots of the ESS from the fit to Australian catch-at-size with respect to model uncertainty factors.

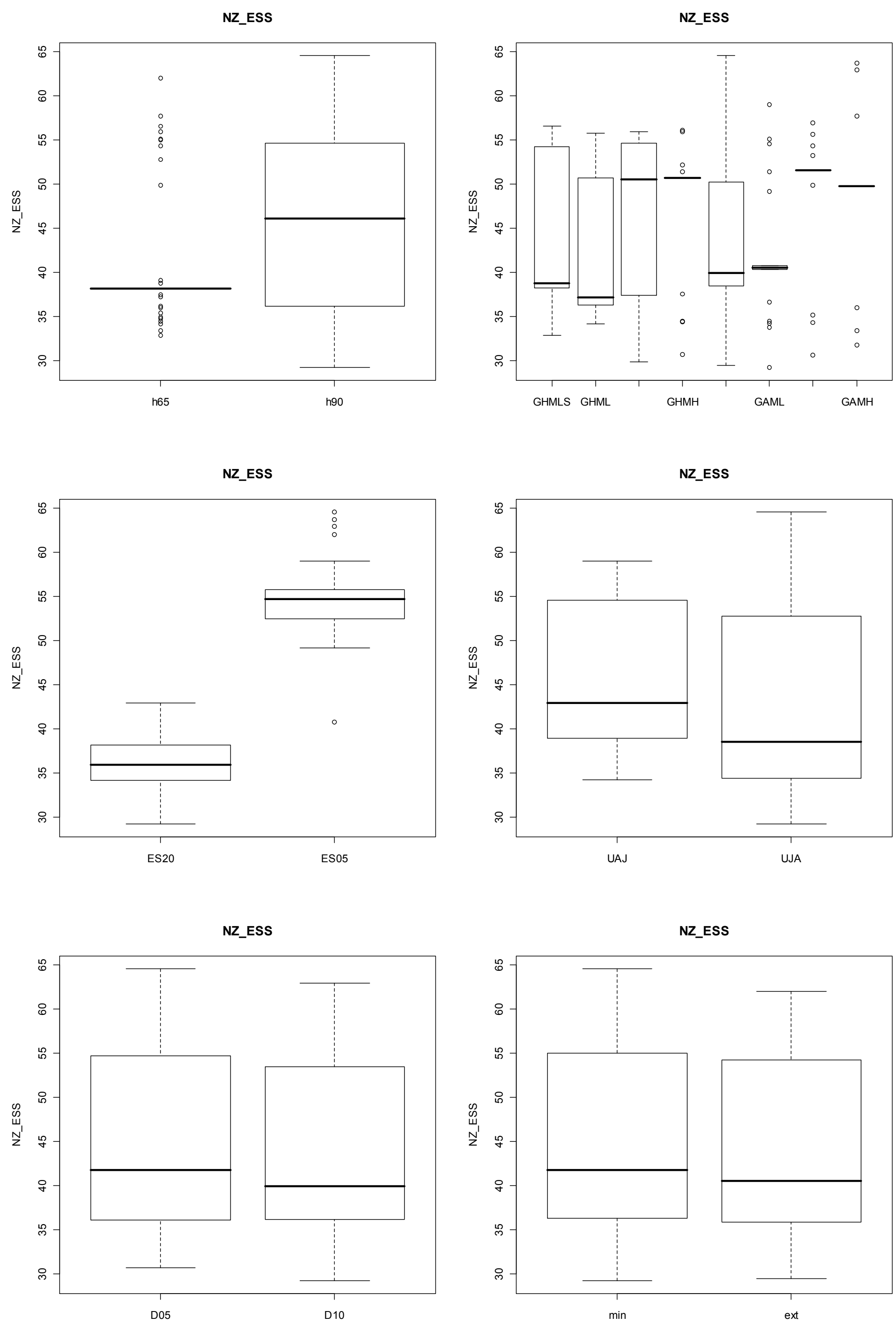


Figure 14: Boxplots of the ESS from the fit to New Zealand catch-at-size with respect to model uncertainty factors.

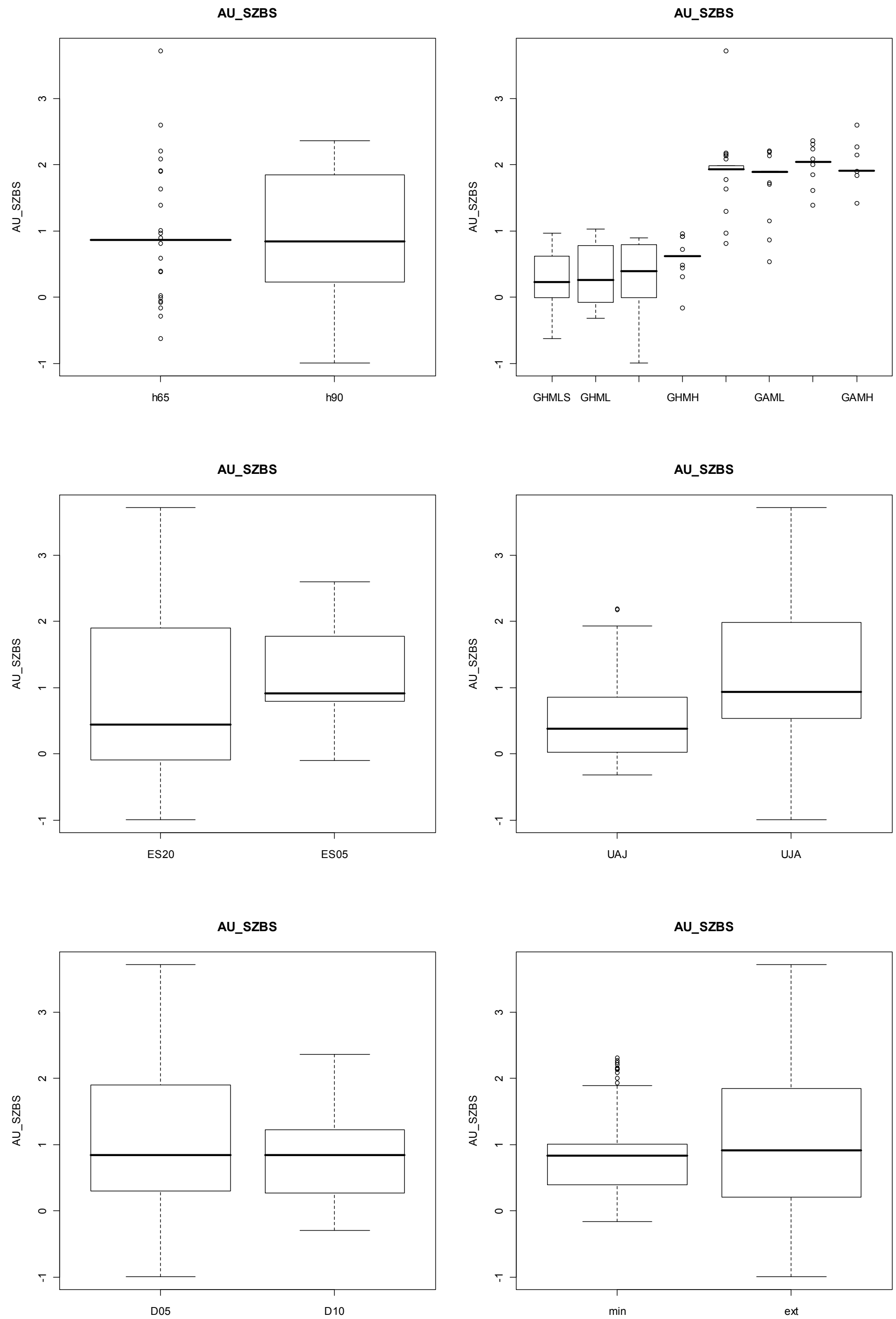


Figure 15: Boxplots of the mean size bias from the fit to Australian catch-at-size with respect to model uncertainty factors.

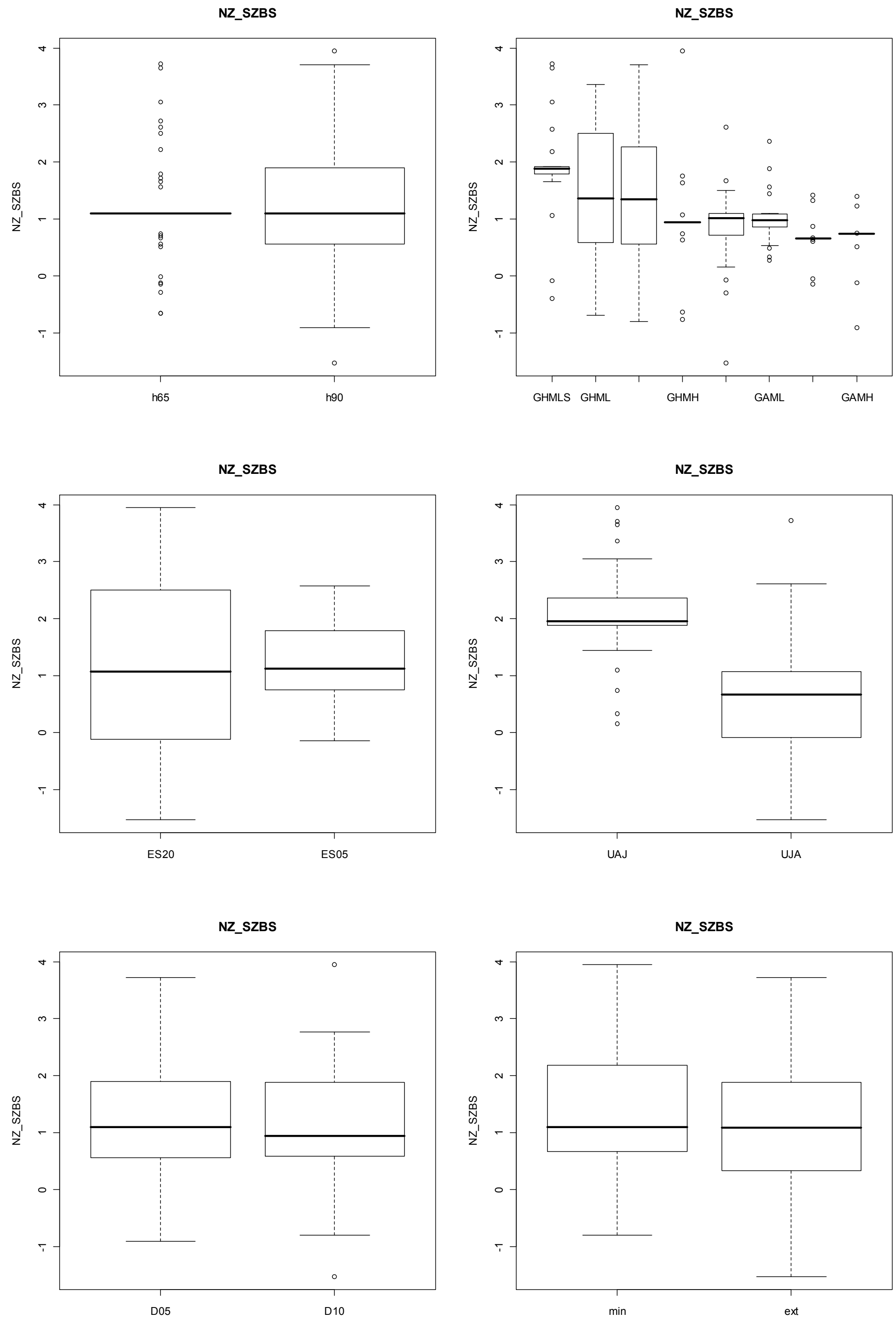


Figure 16: Boxplots of the mean size bias from the fit to New Zealand catch-at-size with respect to model uncertainty factors.

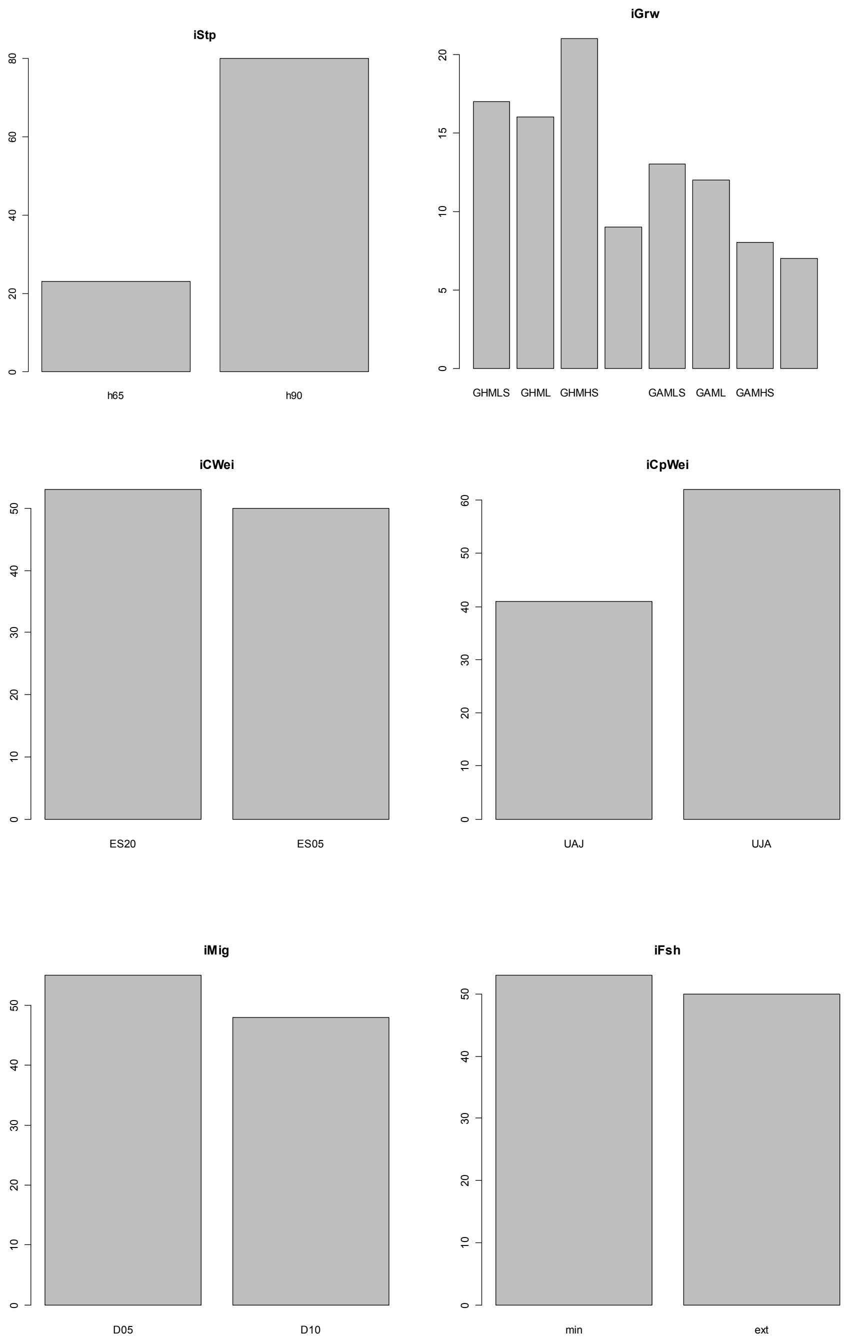


Figure 17: Histograms of the frequency of uncertainty factors making up the subset of 103 models.

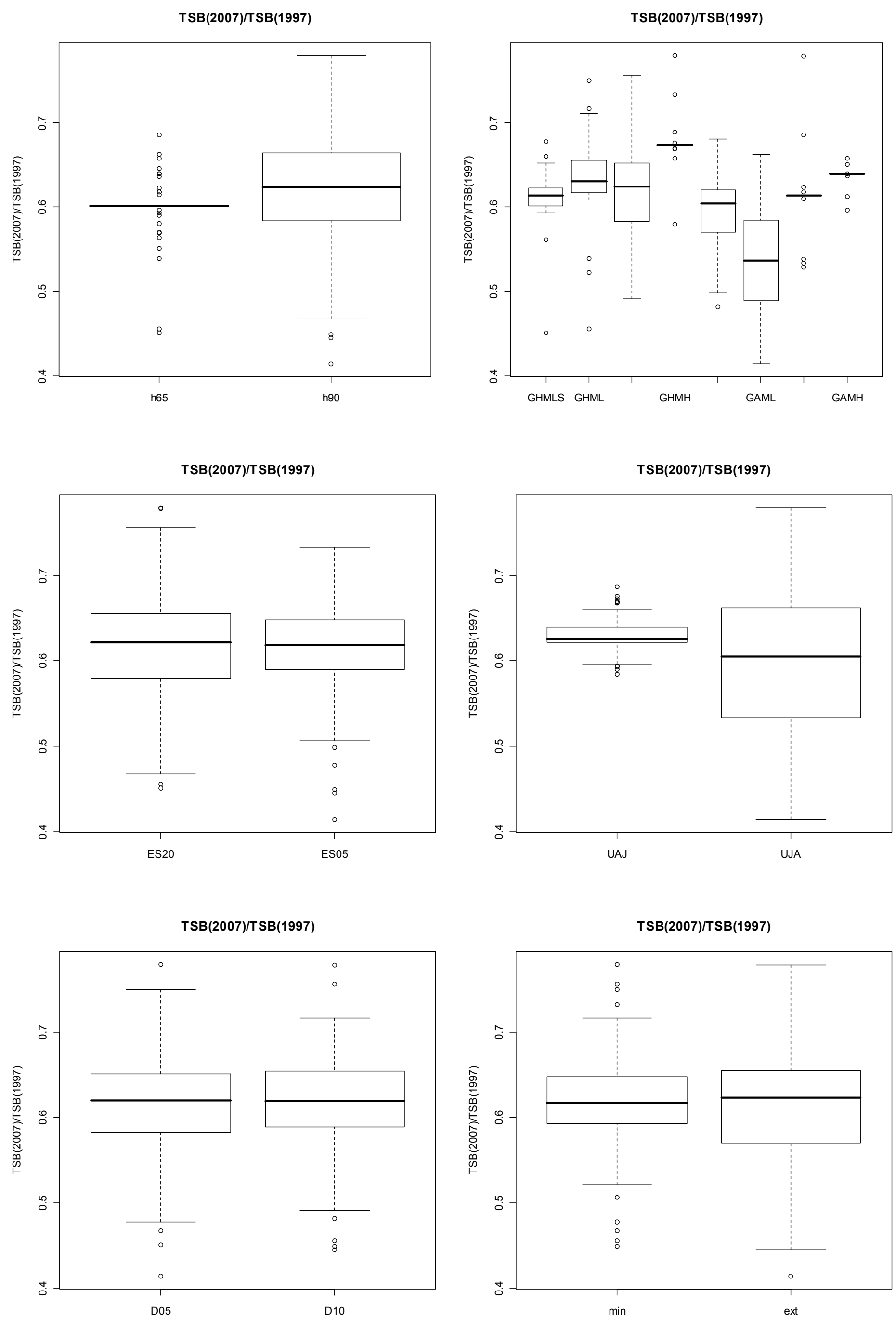


Figure 18: Boxplots of estimates of total stock biomass in 2007 relative to that in 1997, TSB(2007)/TSB(1997) for the subset of 103 models.

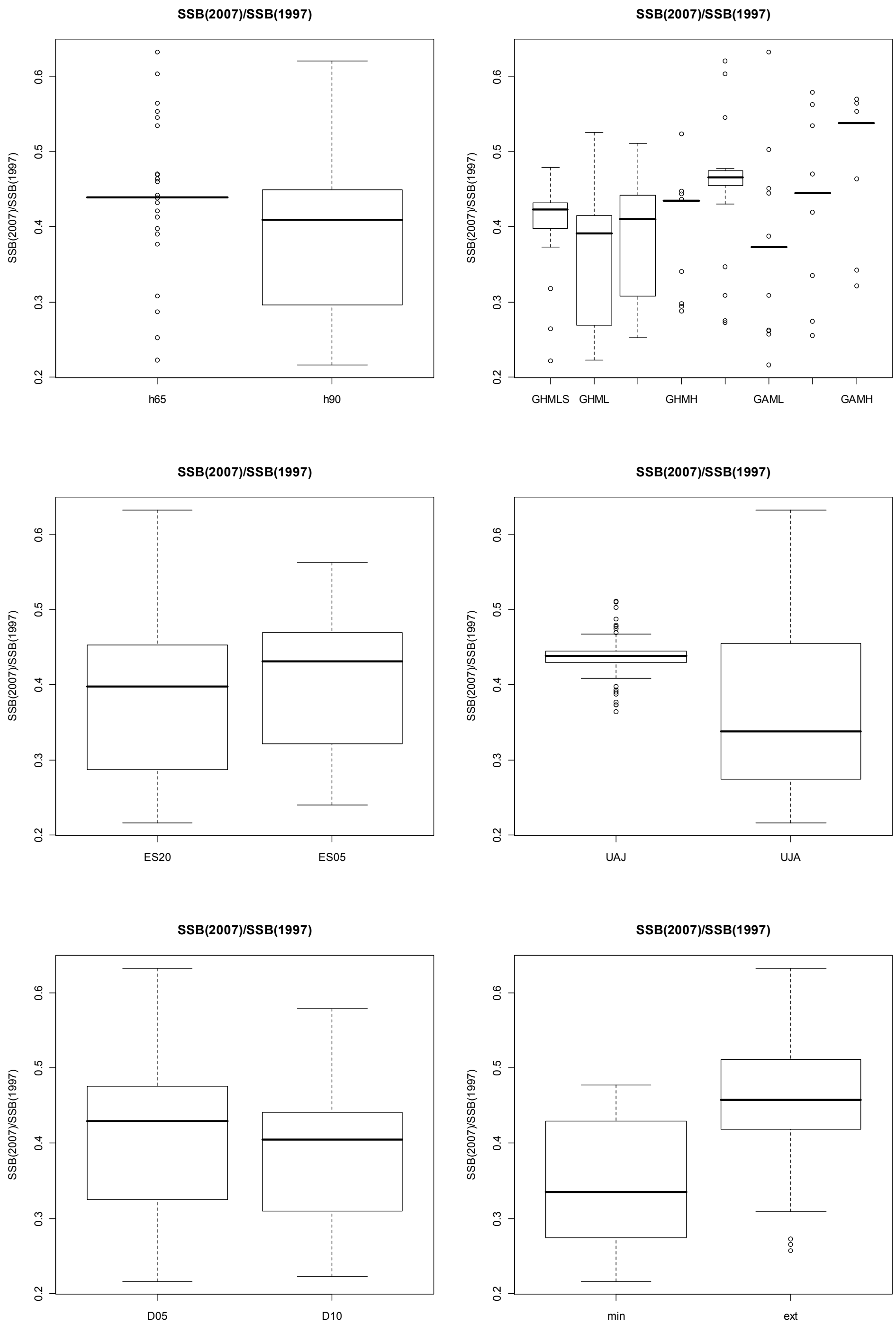


Figure 19: Boxplots of estimates of spawning stock biomass in 2007 relative to that in 1997, SSB(2007)/SSB(1997) for the subset of 103 models.

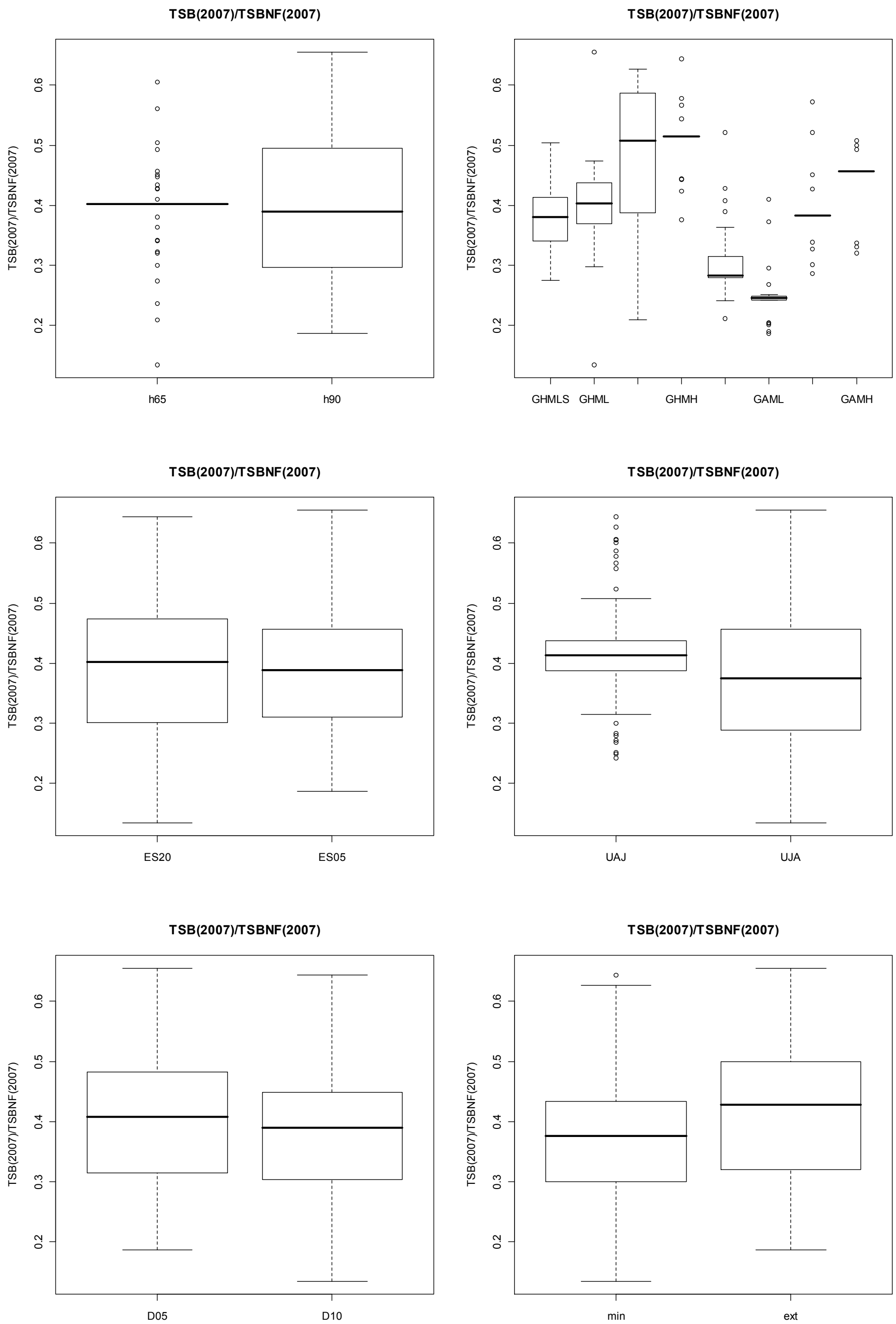


Figure 20: Boxplots of estimates of total stock biomass in 2007 relative to that of the unfished population, TSB(2007)/TSBNF(2007) for the subset of 103 models.

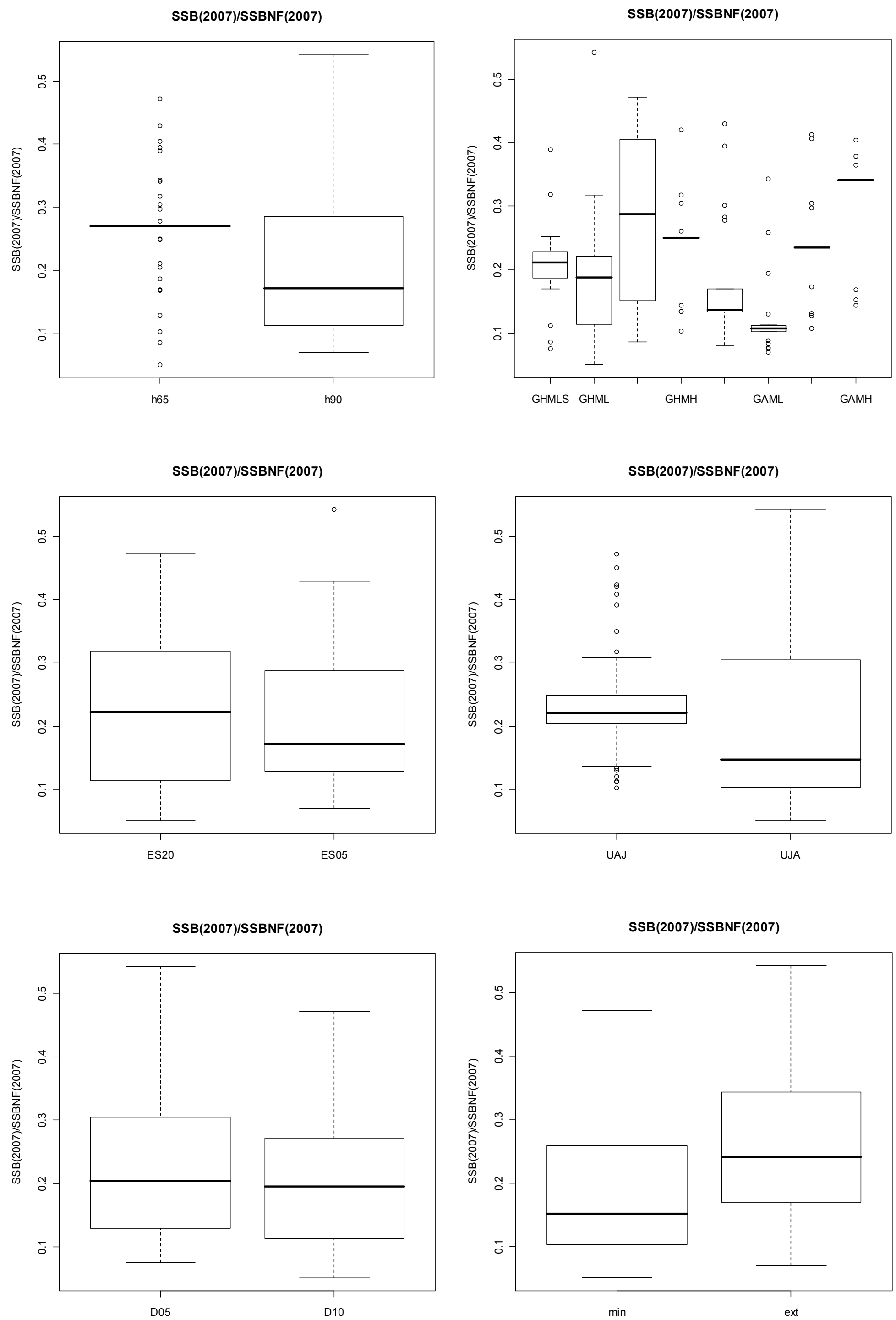


Figure 21: Boxplots of estimates of spawning stock biomass in 2007 relative to that of the unfished population, SSB(2007)/SSBNF(2007) for the subset of 103 models.

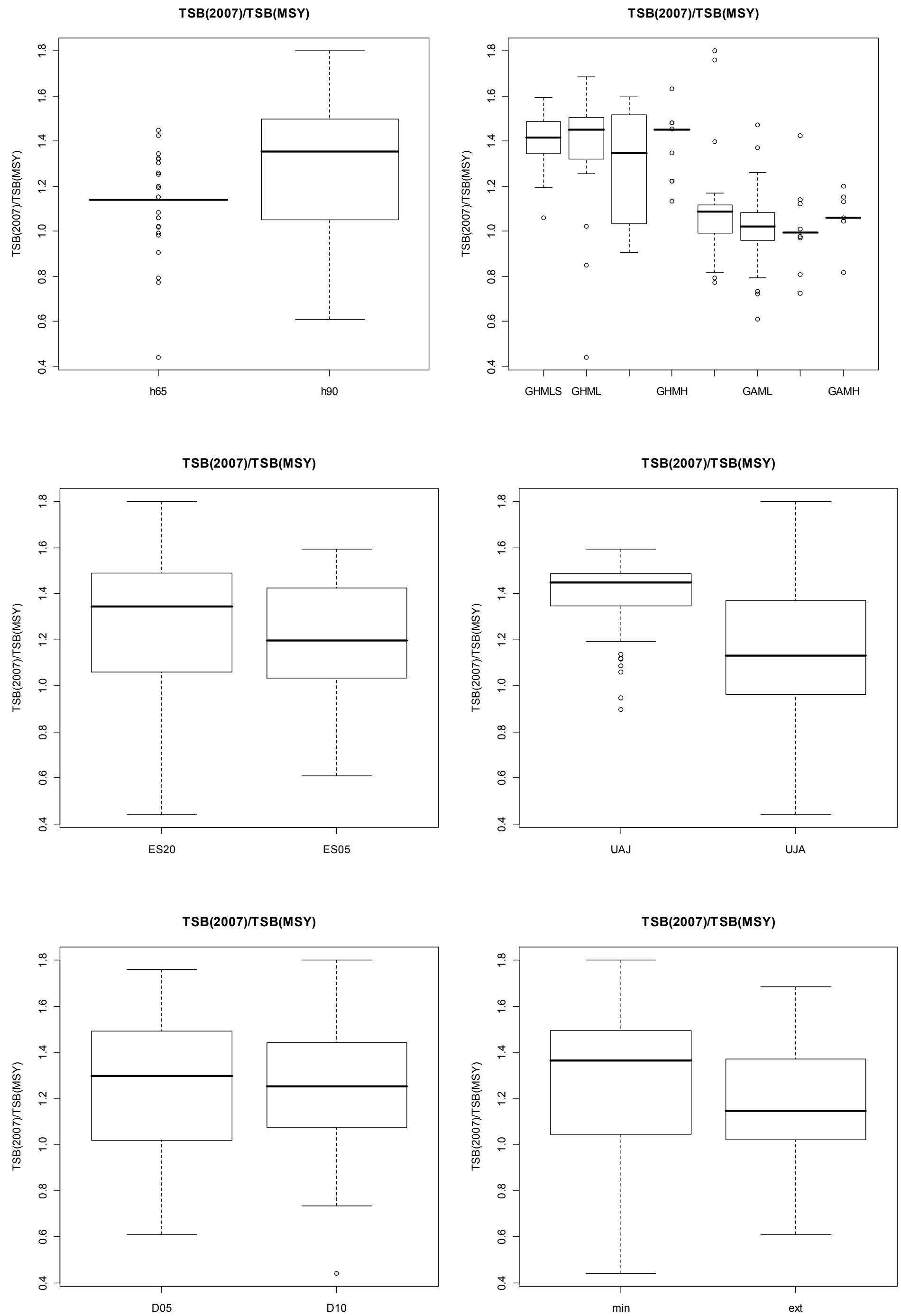


Figure 22: Boxplots of estimates of total stock abundance (numbers of fish) in 2007 relative to that at a stock size that supports maximum sustainable yield (in numbers of fish), TSB(2007)/TSB(MSY) for the subset of 103 models.

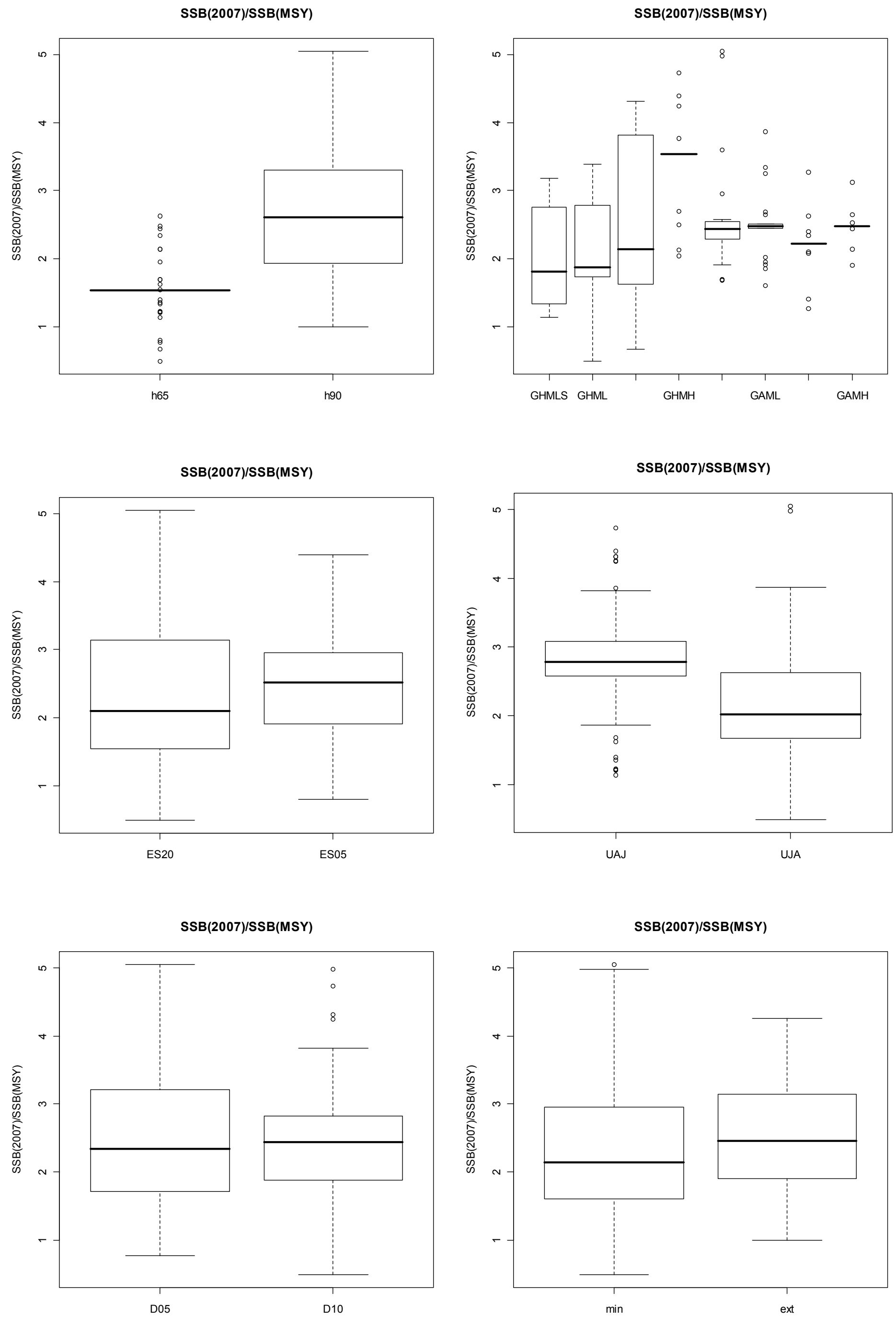


Figure 23: Boxplots of estimates of spawning stock abundance (numbers of fish) in 2007 relative to that at a stock size that supports maximum sustainable yield (in numbers of fish), SSB(2007)/SSB(MSY) for the subset of 103 models.

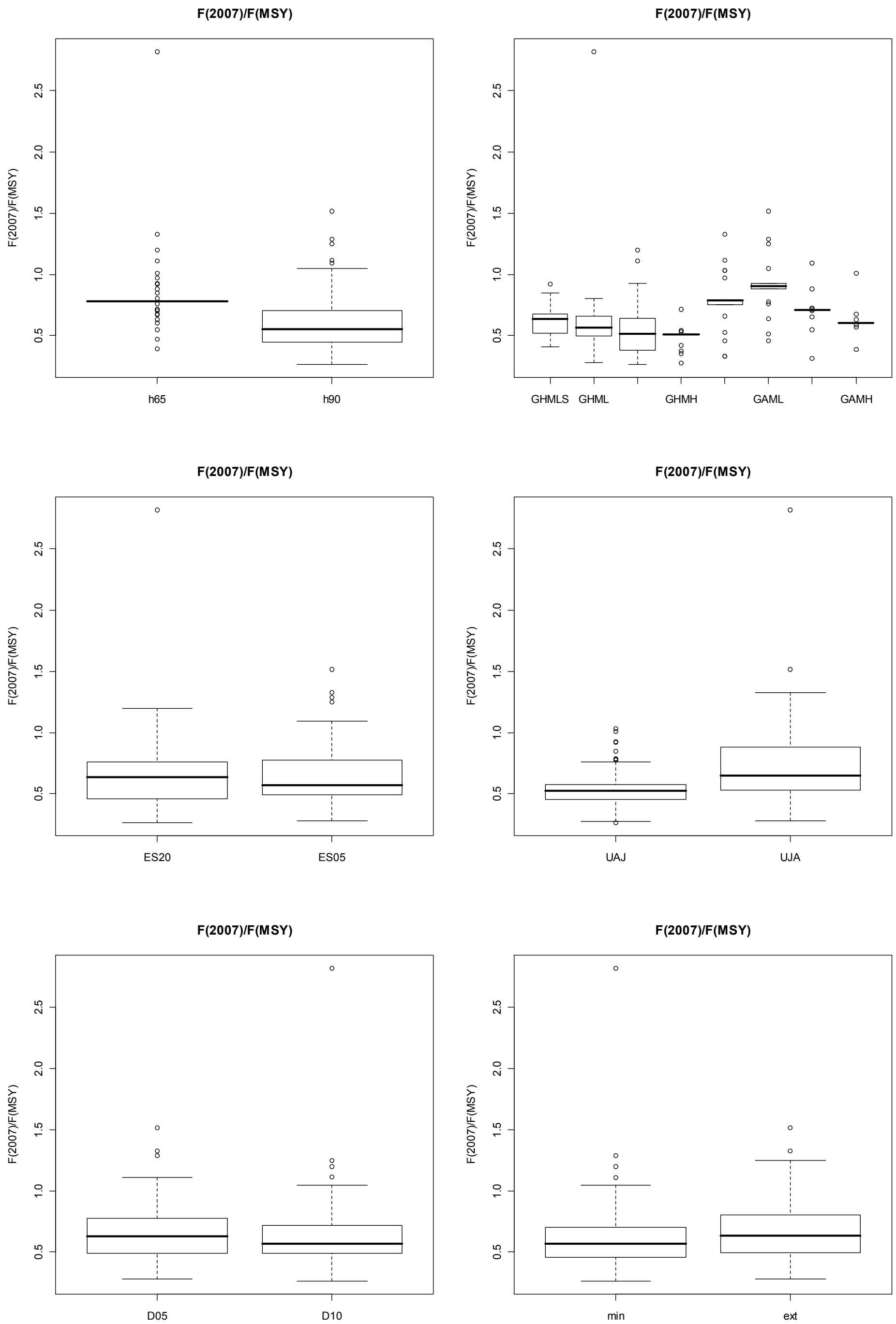


Figure 24: Boxplots of estimates of exploitation rate (in numbers of fish) in 2007 relative to that occurring at an equilibrium stock size that supports maximum sustainable yield (in numbers of fish), F(2007)/F(MSY) for the subset of 103 models.

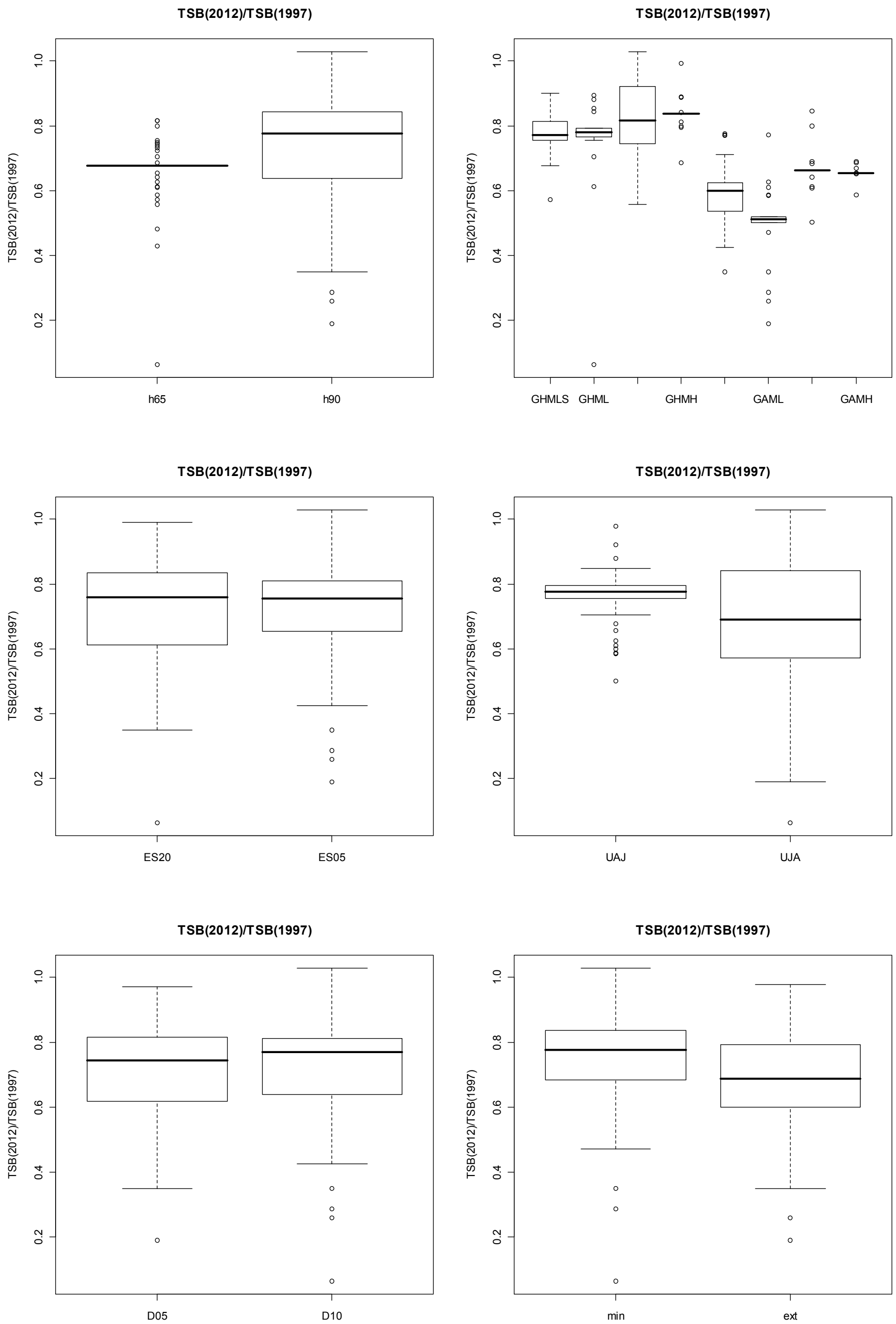


Figure 25: Boxplots of estimates of predicted total stock biomass in 2012 relative to that estimated in 1997, TSB(2012)/TSB(1997) for the subset of 103 models.

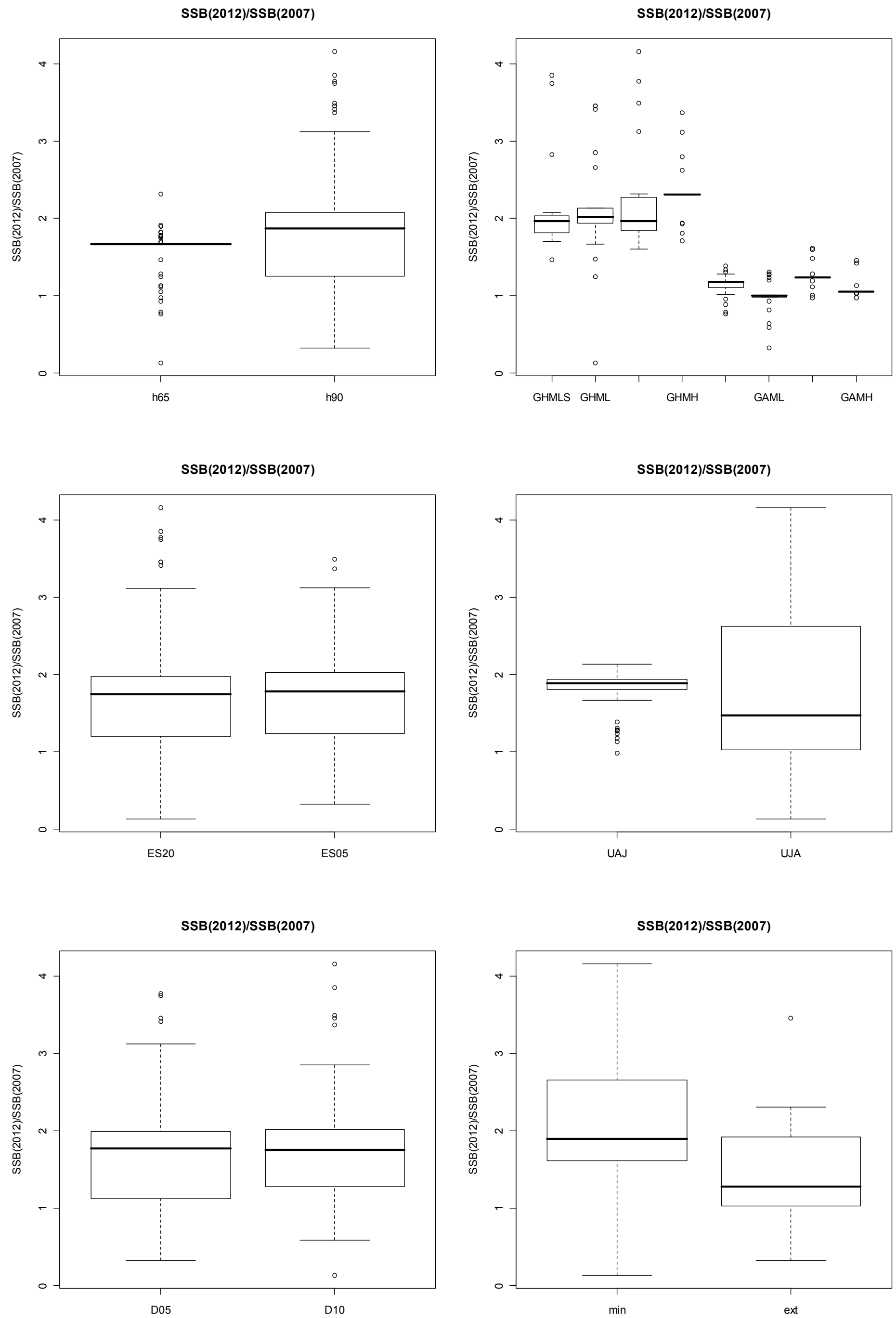


Figure 26: Boxplots of estimates of predicted spawning stock biomass in 2012 relative to that estimated in 2007, SSB(2012)/SSB(2007) for the subset of 103 models.

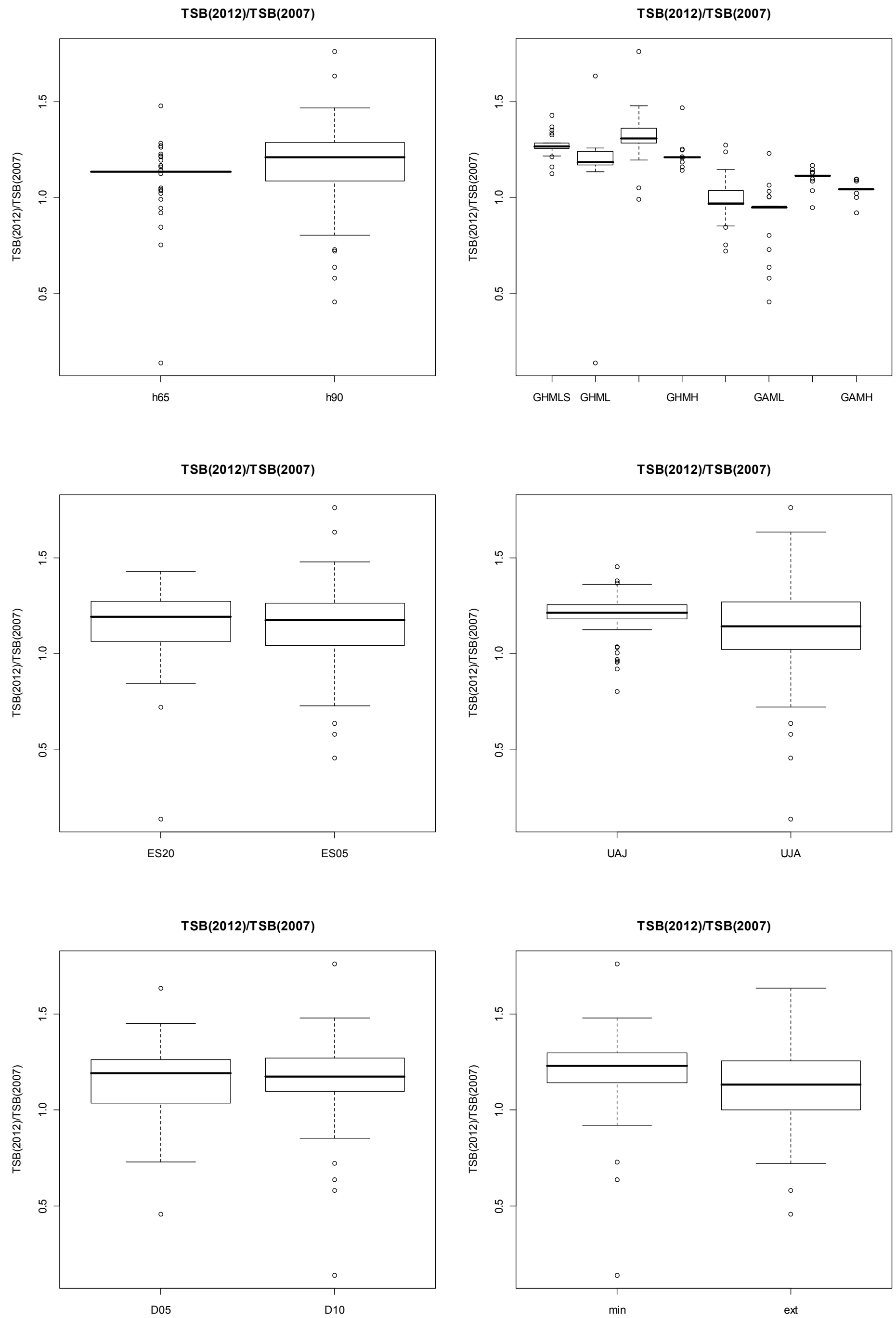


Figure 27: Boxplots of estimates of predicted total stock biomass in 2012 relative to that estimated in 2007, TSB(2012)/TSB(2007) for the subset of 103 models.

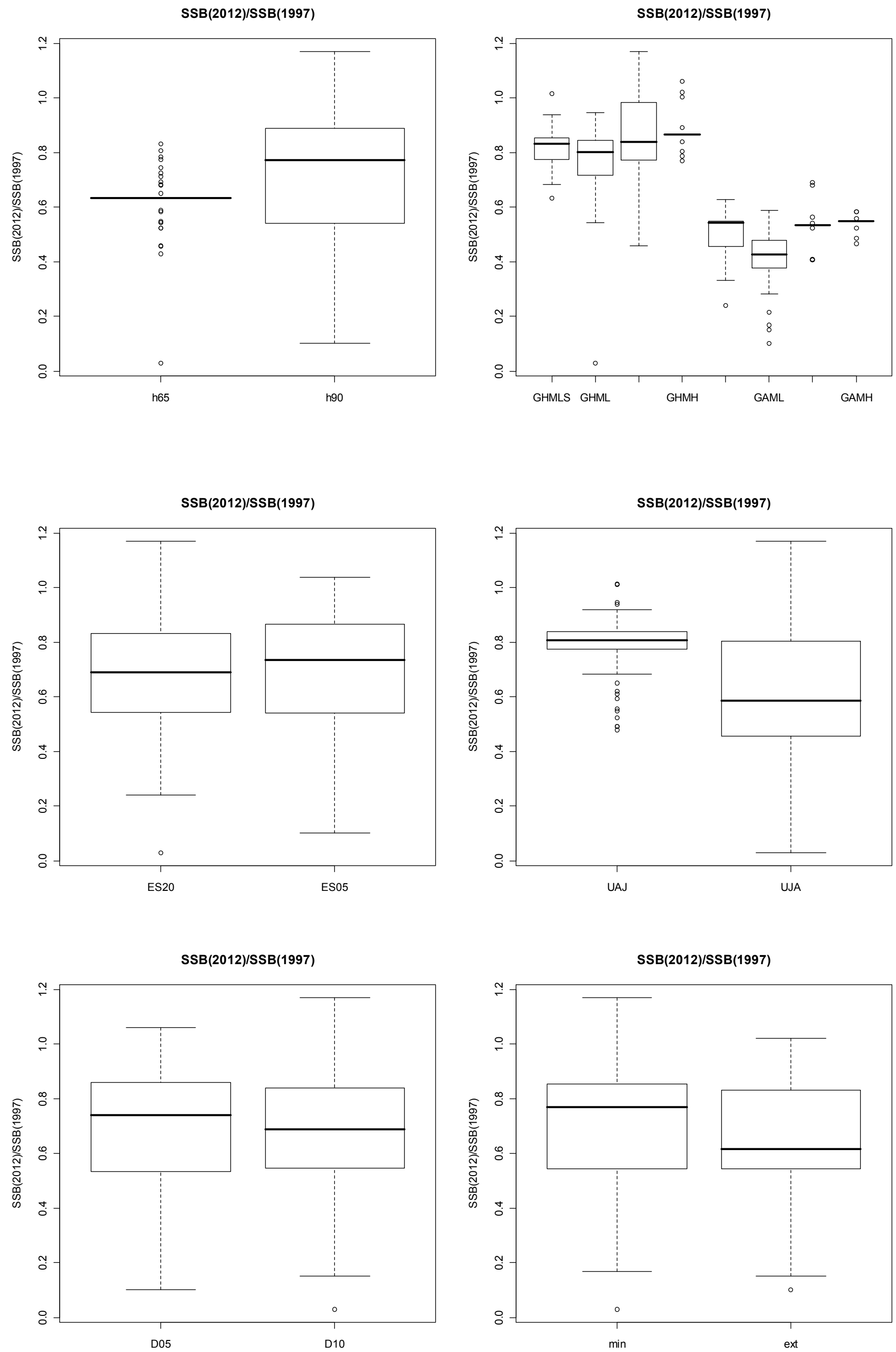


Figure 28: Boxplots of estimates of predicted spawning stock biomass in 2012 relative to that estimated in 1997, SSB(2012)/SSB(1997) for the subset of 103 models.

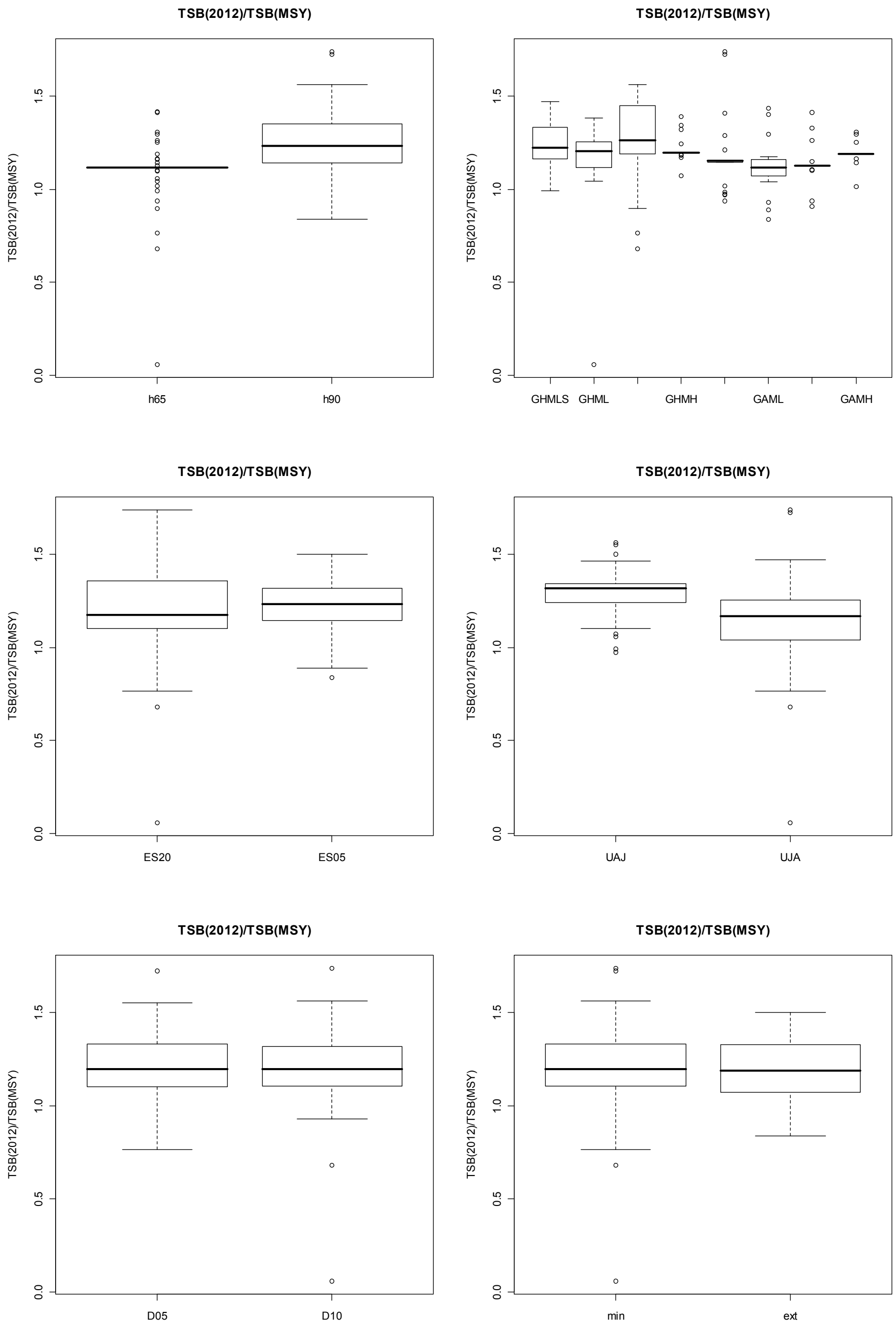


Figure 29: Boxplots of estimates of predicted total stock abundance (numbers of fish) in 2012 relative to that at a stock size that supports maximum sustainable yield (in numbers of fish), TSB(2012)/TSB(MSY) for the subset of 103 models.

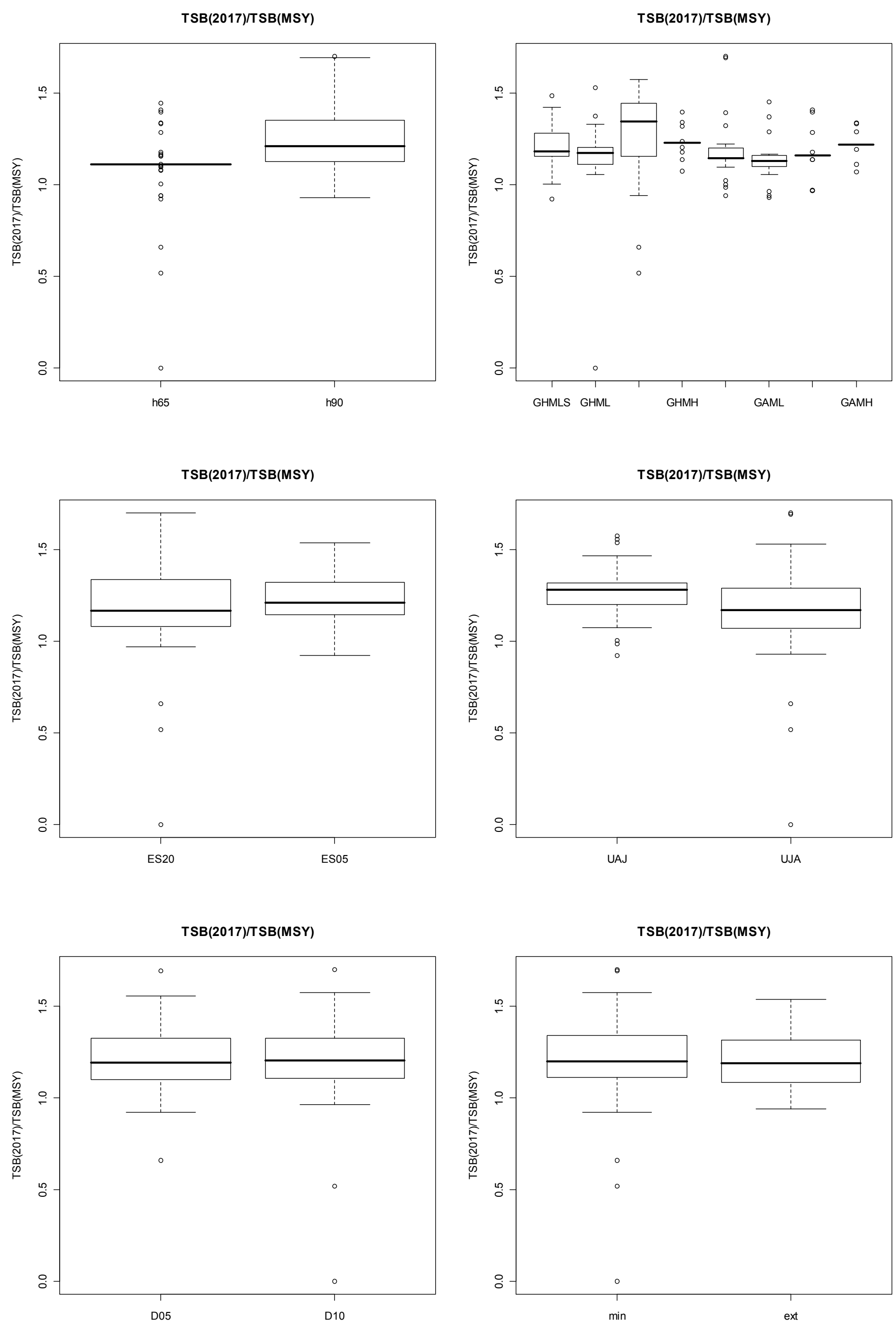


Figure 30: Boxplots of estimates of predicted total stock abundance (numbers of fish) in 2017 relative to that at a stock size that supports maximum sustainable yield (in numbers of fish), TSB(2017)/TSB(MSY) for the subset of 103 models.

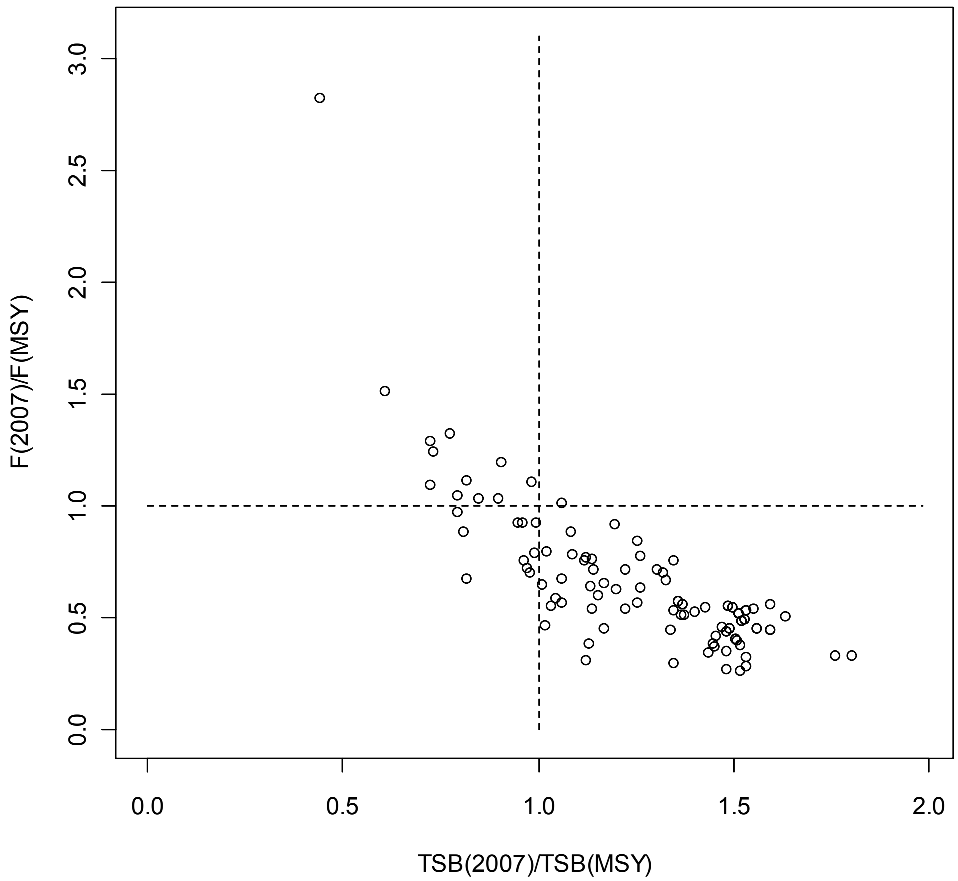


Figure 31: Scatterplot of estimates of exploitation rate (in numbers of fish) in 2007 relative to that occurring at an equilibrium stock size that supports maximum sustainable yield (in numbers of fish), F(2007)/F(MSY) versus the estimates of total stock abundance (numbers of fish) in 2007 relative to that at a stock size that supports maximum sustainable yield (in numbers of fish), TSB(2007)/TSB(MSY) for the subset of 103 models.

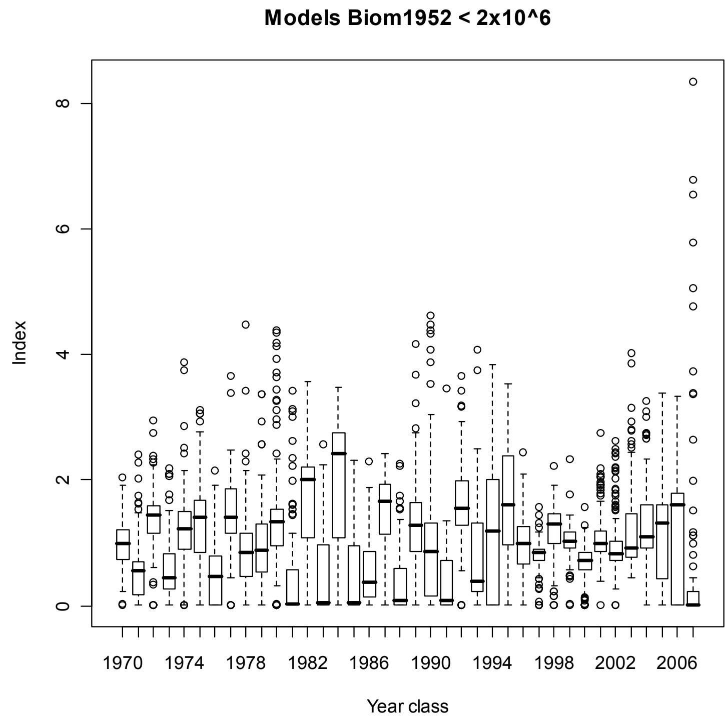
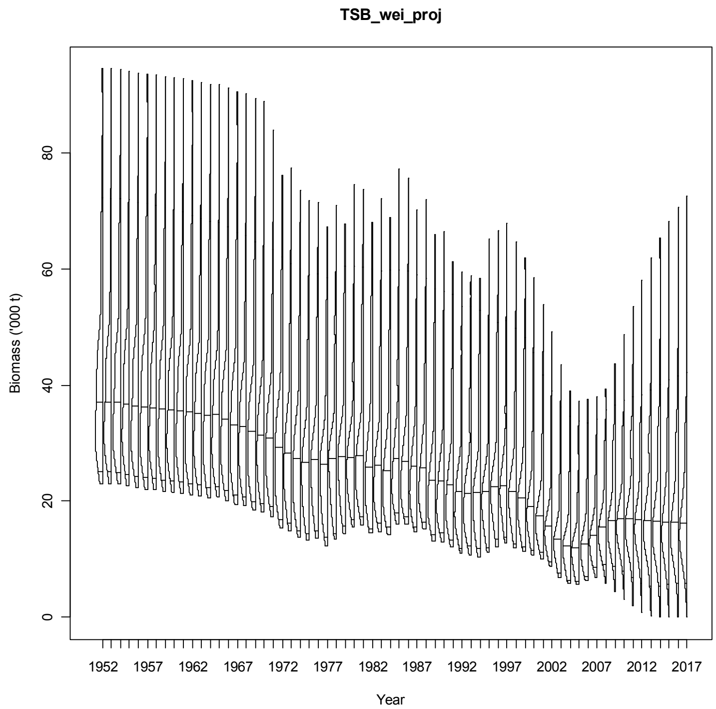


Figure 32: Boxplot of year class strength estimates for the subset of 103 models.



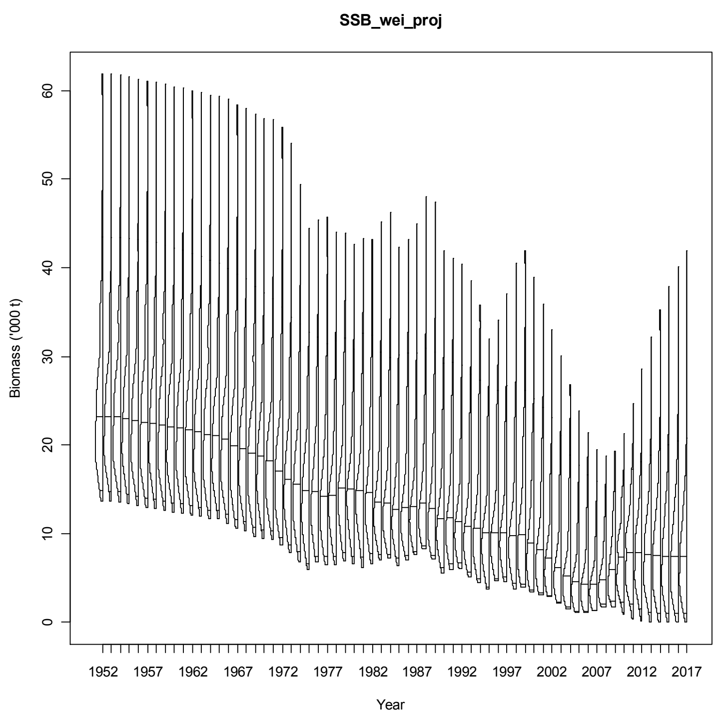


Figure 33: Density functions for the total stock and spawning stock biomass (TSB and SSB respectively) trajectories for 1952 to 2017, for the set of 103 models. Horizontal lines are the 2.5%, 50%, and 97.5% percentiles.

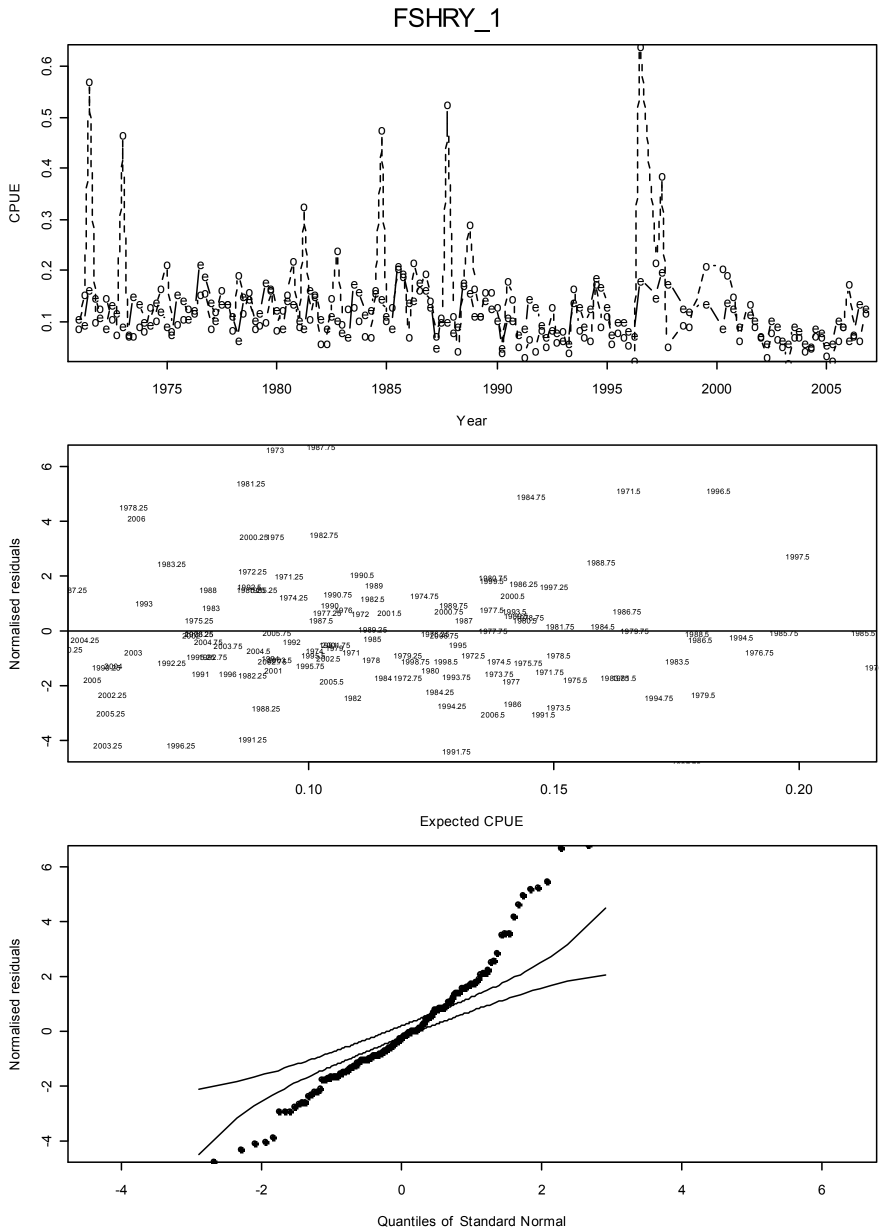


Figure 34: Swordfish CPUE for the DP fishery in area 1, zone 1 (spatial option 2ar) showing observed (-o-) and fitted (-e-) values (top panel) for an example model, with diagnostic plots of the normalised residuals (bottom two panels).

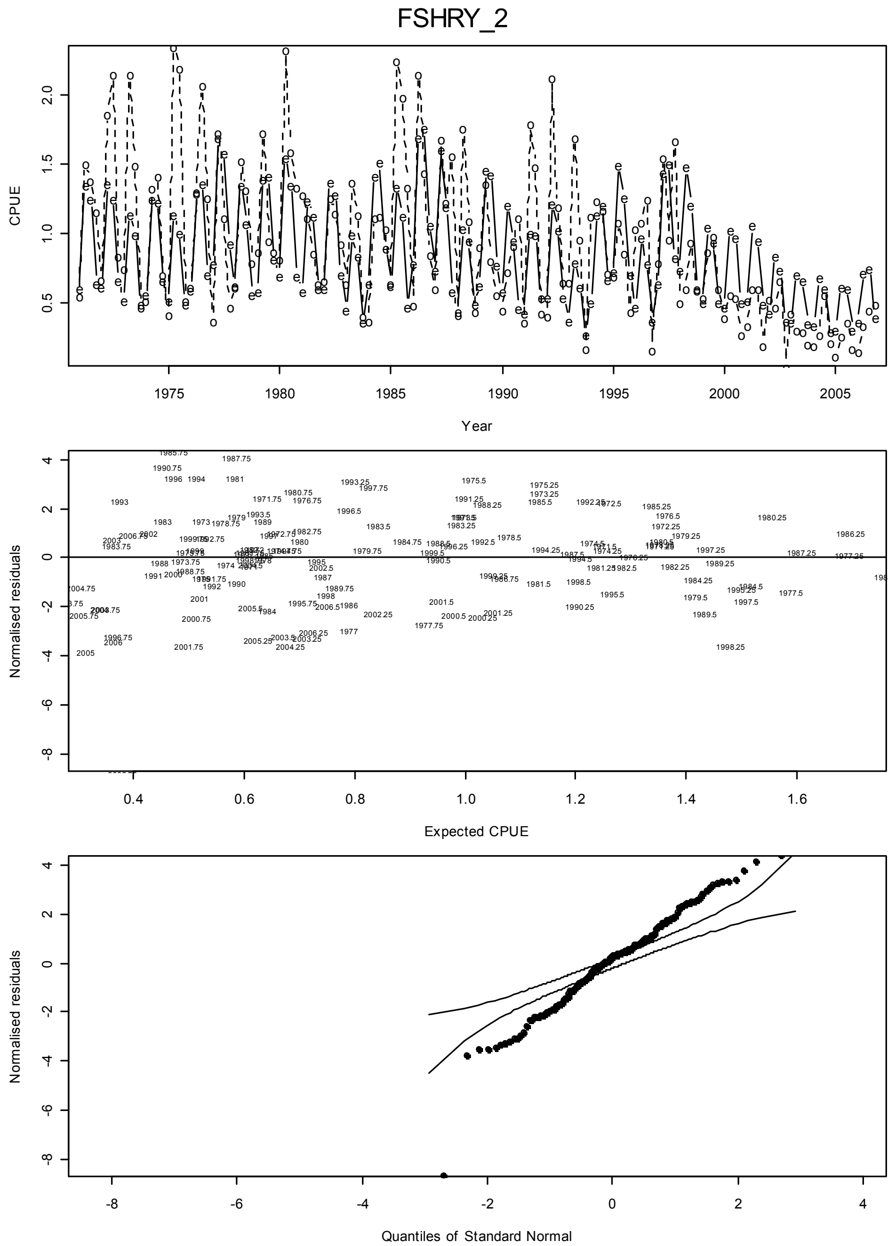


Figure 35: Swordfish CPUE for the DP fishery in area 1, zone 2 (spatial option 2ar) showing observed (-o-) and fitted (-e-) values (top panel) for an example model, with diagnostic plots of the normalised residuals (bottom two panels).

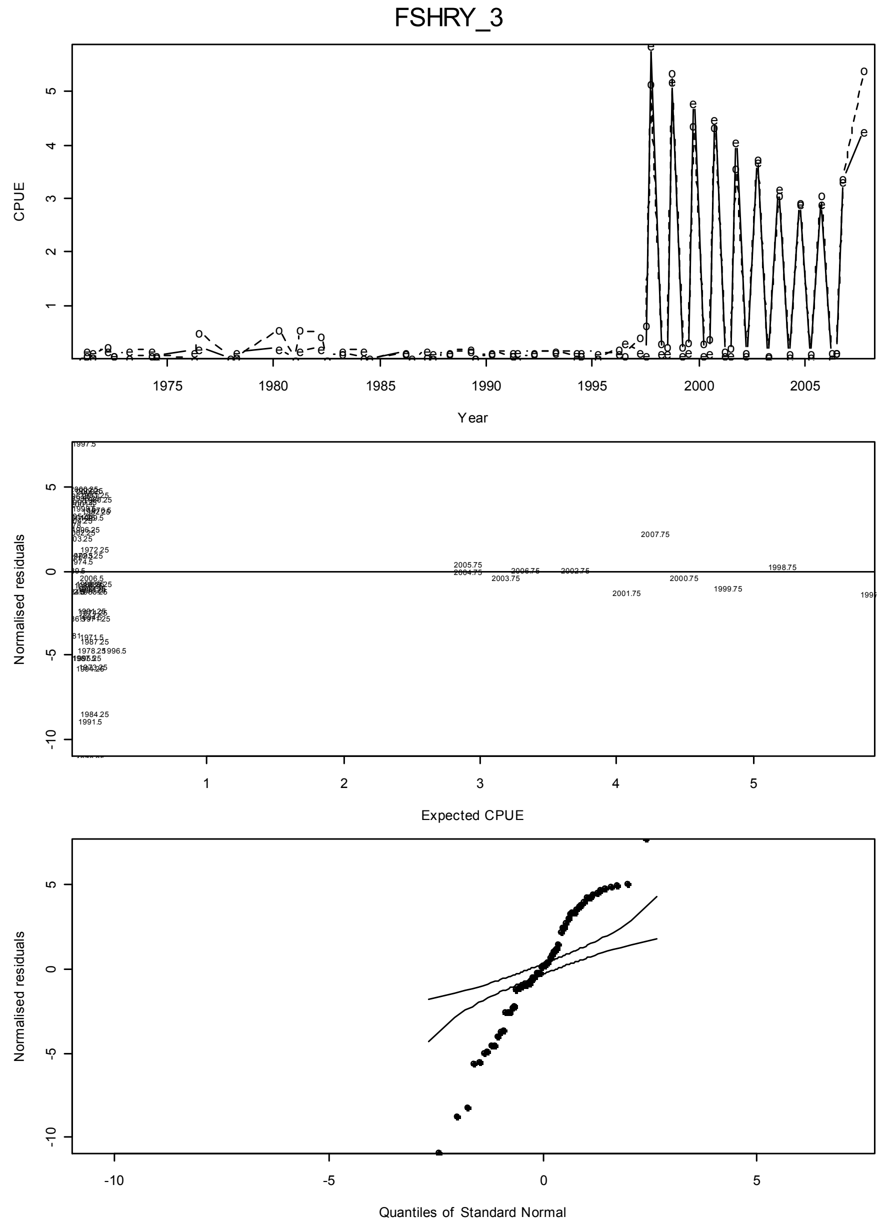


Figure 36: Swordfish CPUE for the DP fishery in area 1, zone 3 (spatial option 2ar) showing observed (-o-) and fitted (-e-) values (top panel) for an example model, with diagnostic plots of the normalised residuals (bottom two panels).

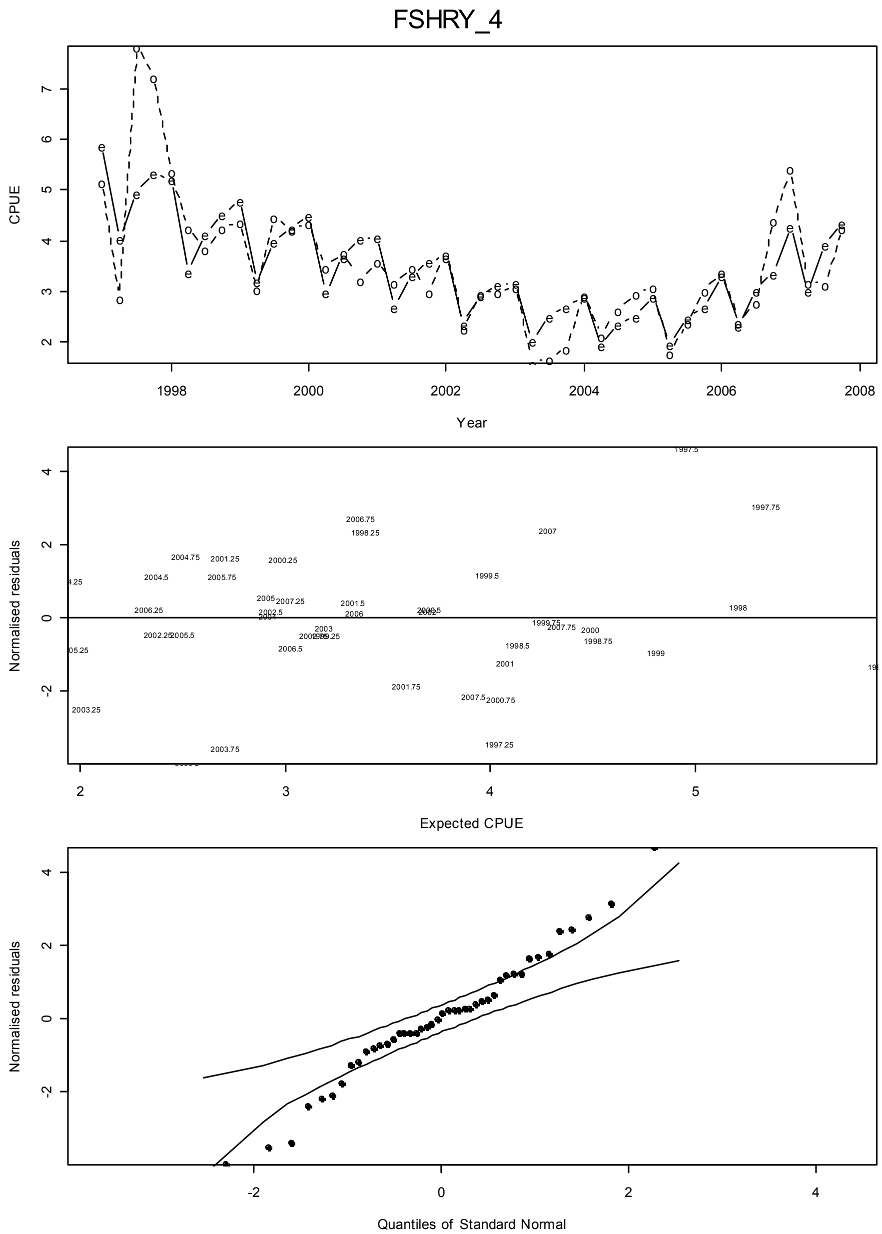


Figure 37: Swordfish CPUE for the AU fishery in area 1, zone 2 (spatial option 2ar) showing observed (-o-) and fitted (-e-) values (top panel) for an example model, with diagnostic plots of the normalised residuals (bottom two panels).

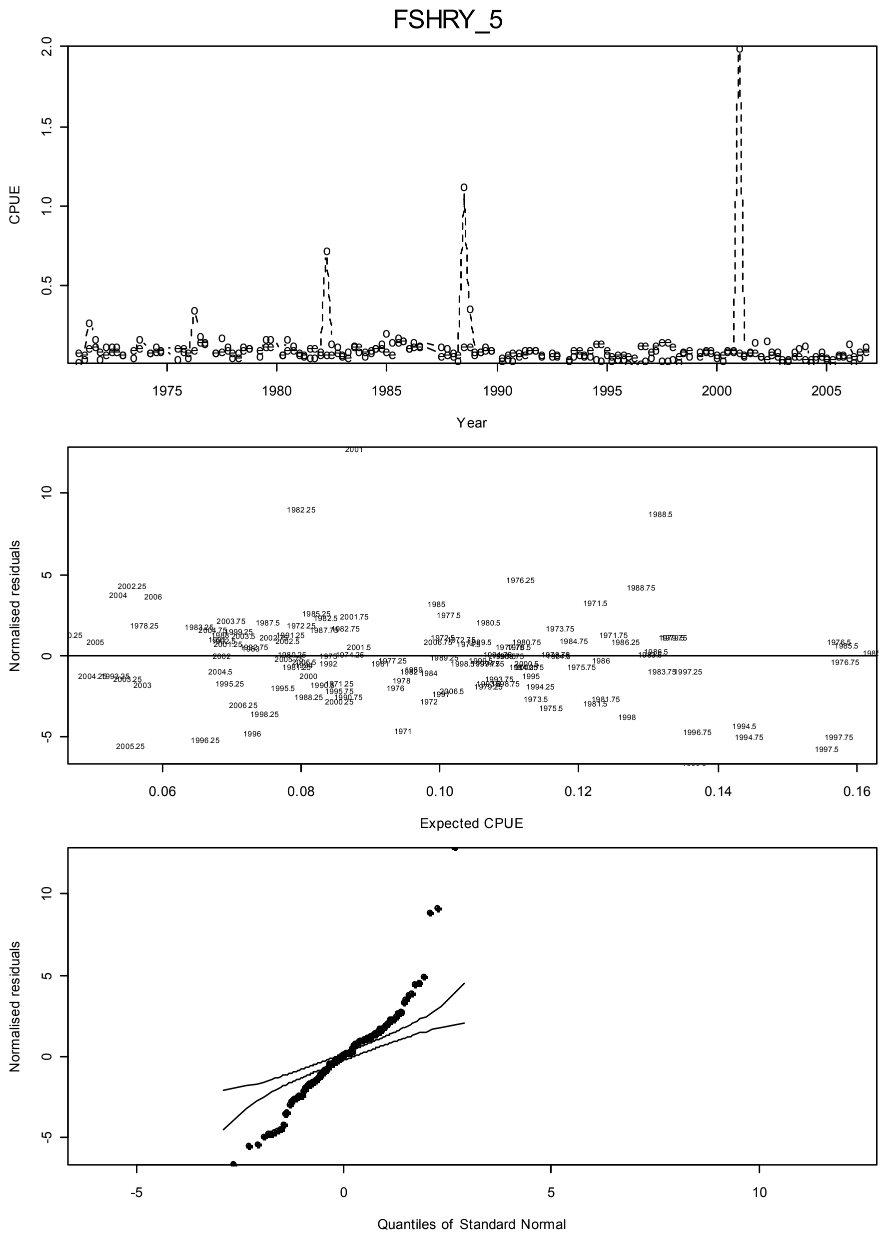


Figure 38: Swordfish CPUE for the DP fishery in area 2, zone 1 (spatial option 2ar) showing observed (-o-) and fitted (-e-) values (top panel) for an example model, with diagnostic plots of the normalised residuals (bottom two panels).

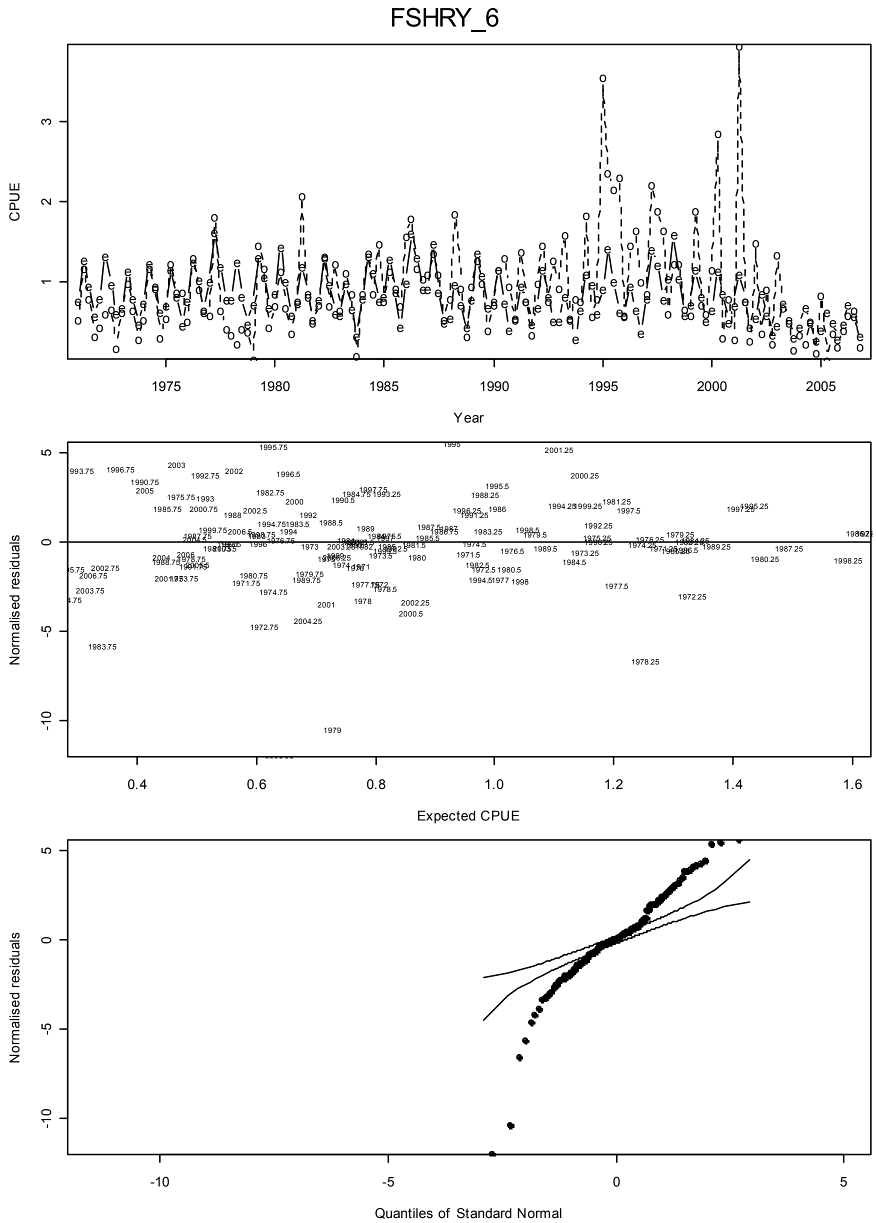


Figure 39: Swordfish CPUE for the DP fishery in area 2, zone 2 (spatial option 2ar) showing observed (-o-) and fitted (-e-) values (top panel) for an example model, with diagnostic plots of the normalised residuals (bottom two panels).

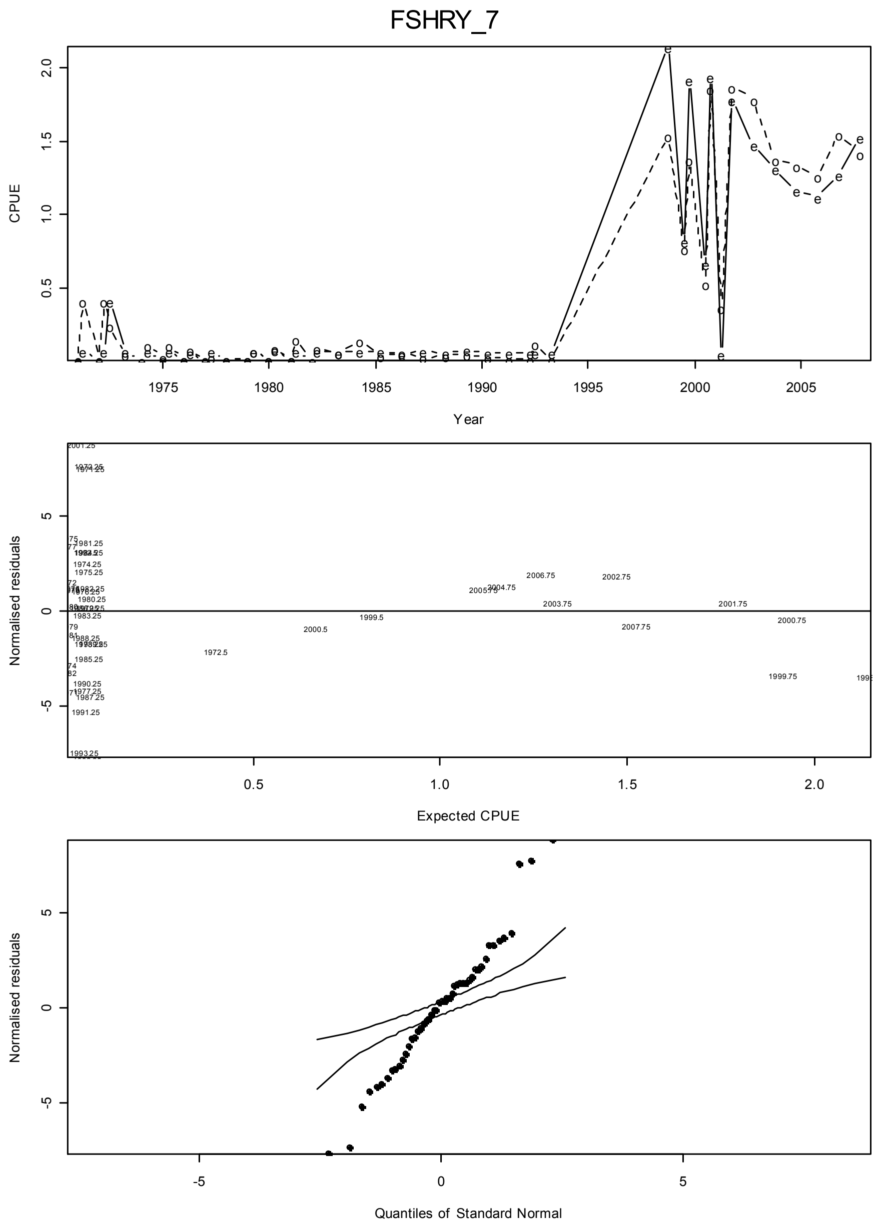


Figure 40: Swordfish CPUE for the DP fishery in area 2, zone 3 (spatial option 2ar) showing observed (-o-) and fitted (-e-) values (top panel) for an example model, with diagnostic plots of the normalised residuals (bottom two panels).

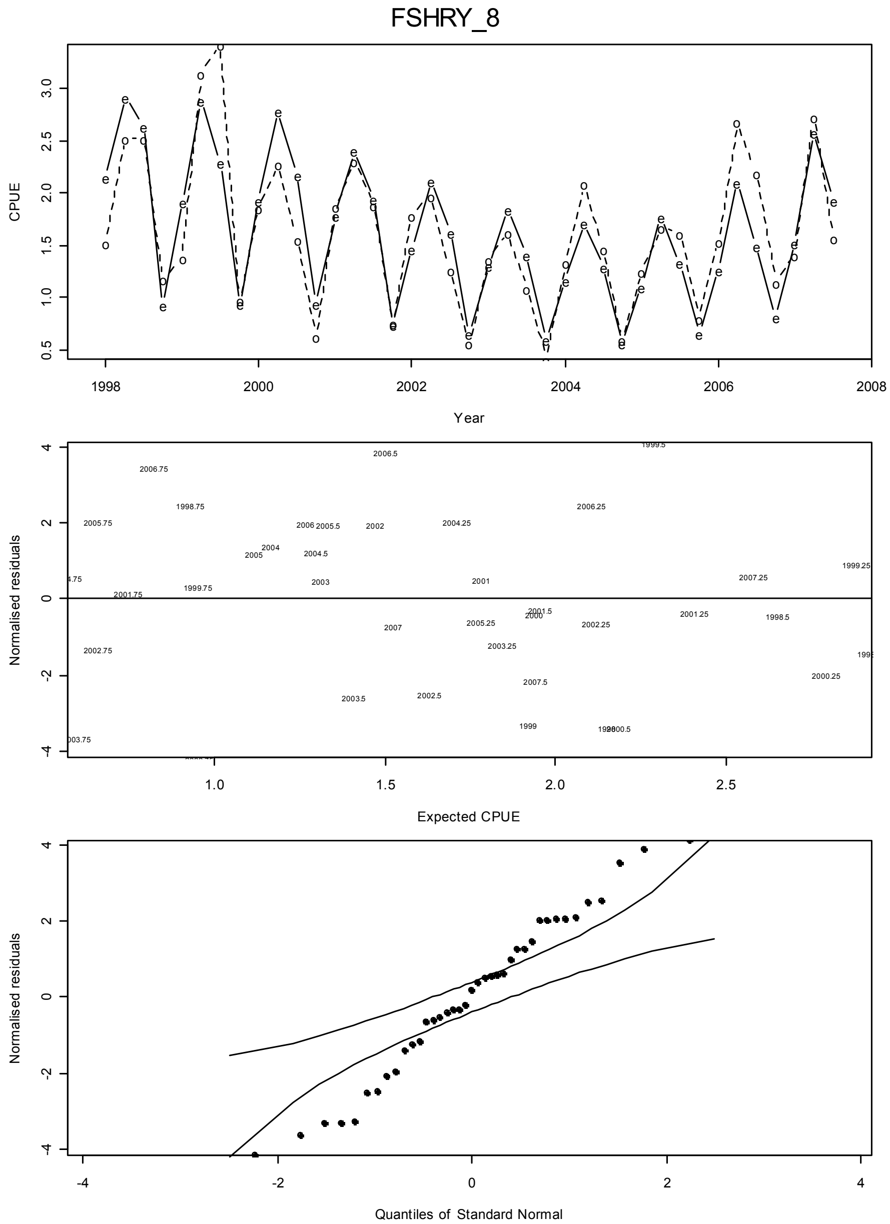


Figure 41: Swordfish CPUE for the NZ fishery in area 2, zone 2 (spatial option 2ar) showing observed (-o-) and fitted (-e-) values (top panel) for an example model, with diagnostic plots of the normalised residuals (bottom two panels).

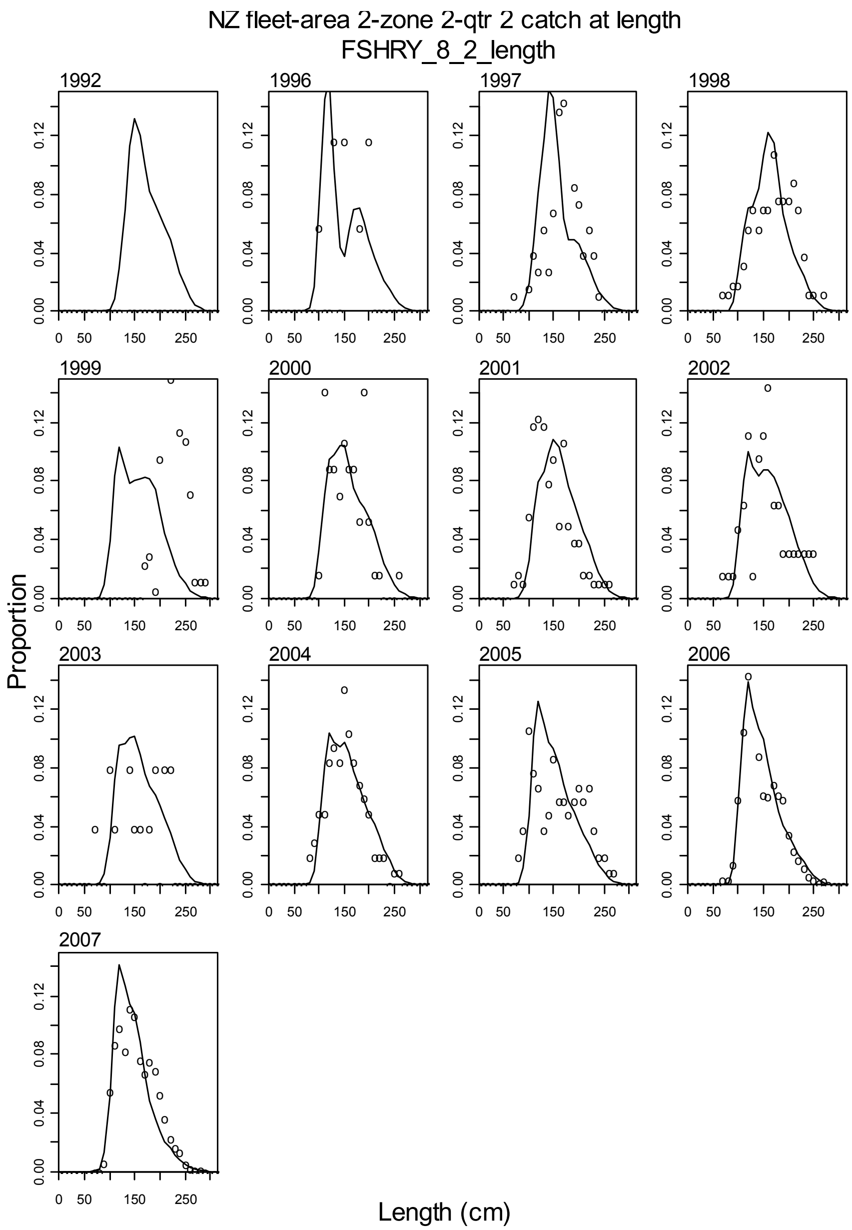


Figure 42: Swordfish catch-at-length time series for the NZ fishery, area 2 zone 2 in the second quarter showing observed (-o-) and fitted (-e-) values for the example model (spatial option 2ar).

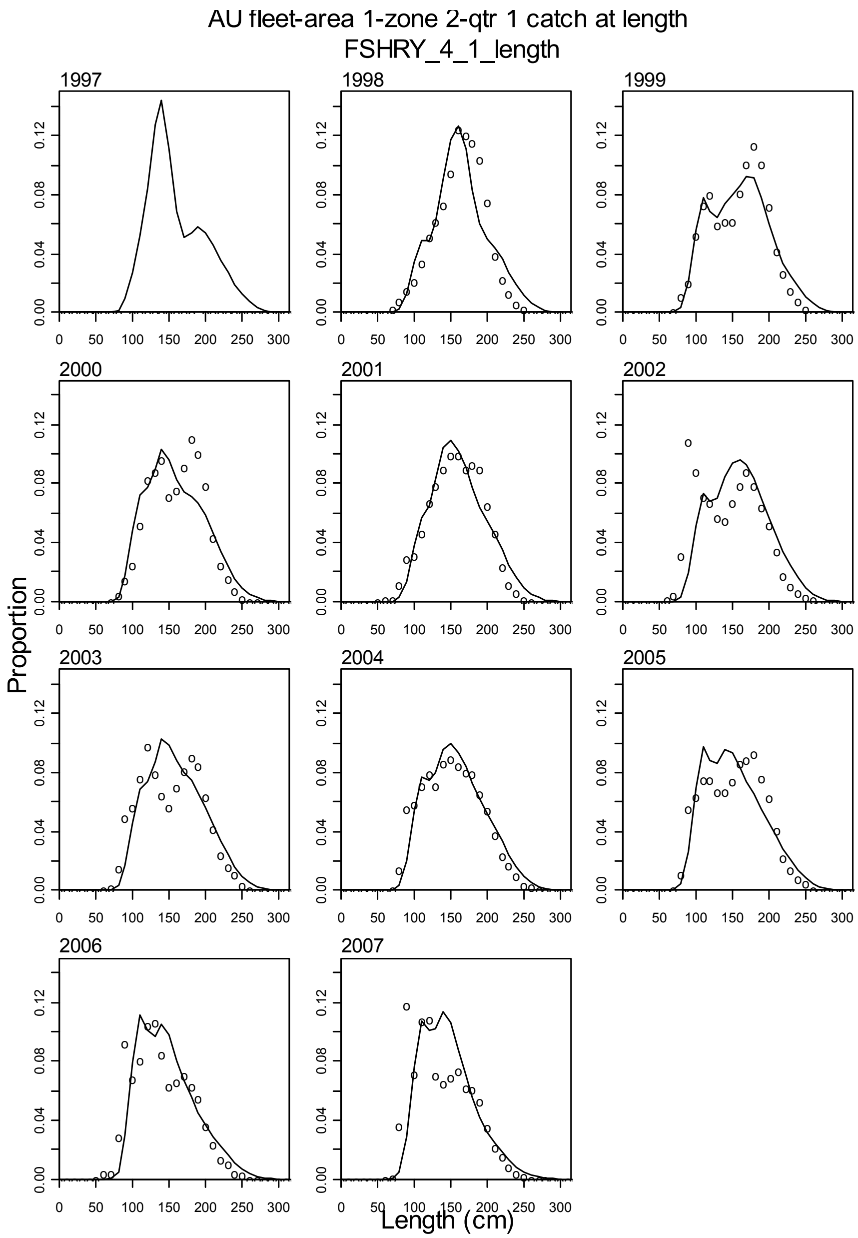


Figure 43: Swordfish catch-at-length time series for the AU fishery, area 1 zone 2 in the first quarter showing observed (-o-) and fitted (-e-) values for the example model (spatial option 2ar).

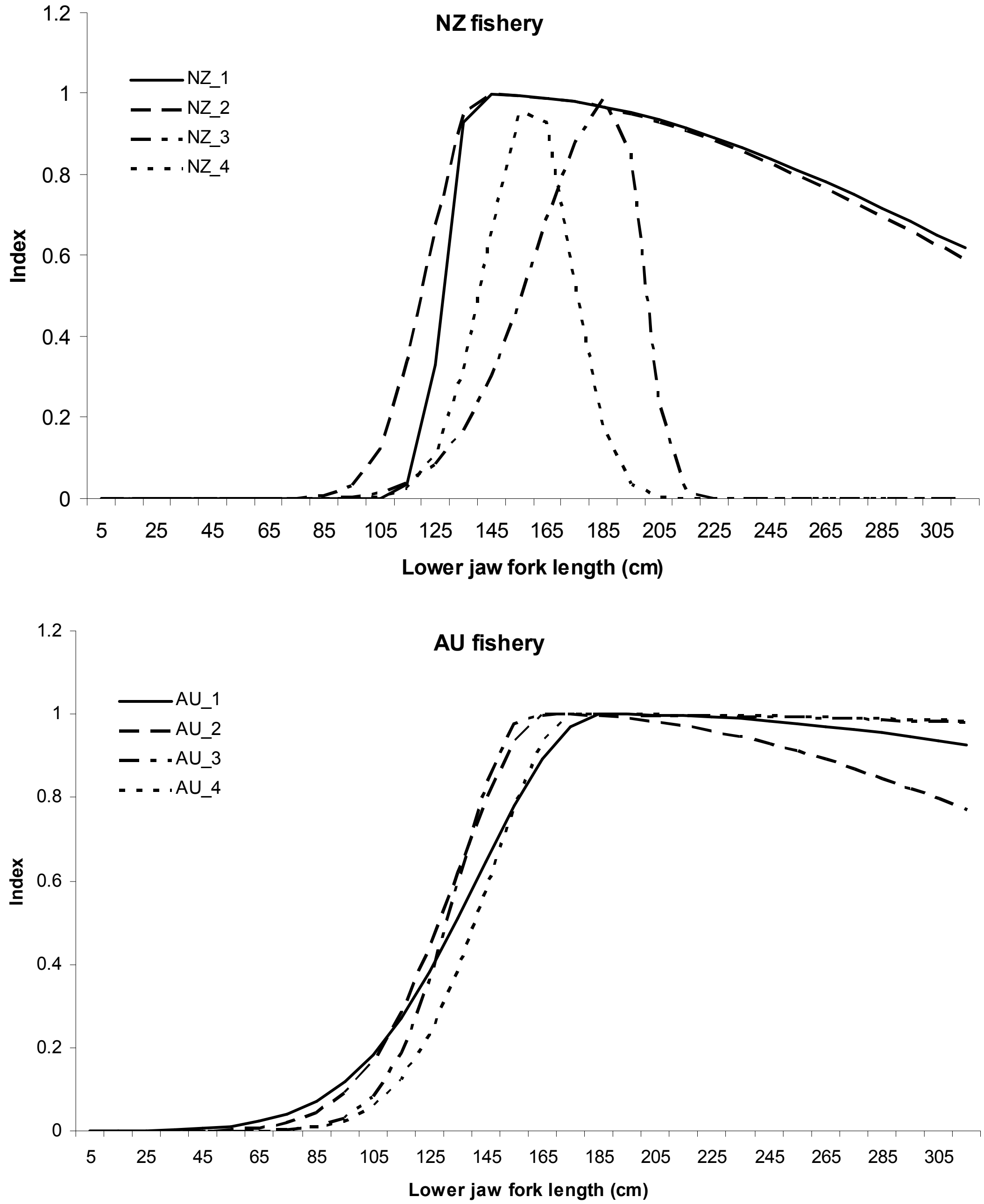


Figure 44: Example model (12211211) estimates of selectivity-at-length for the Australian (AU) and New Zealand (NZ) fisheries in the central zone (2) for each of the four quarters (_1 to _4).

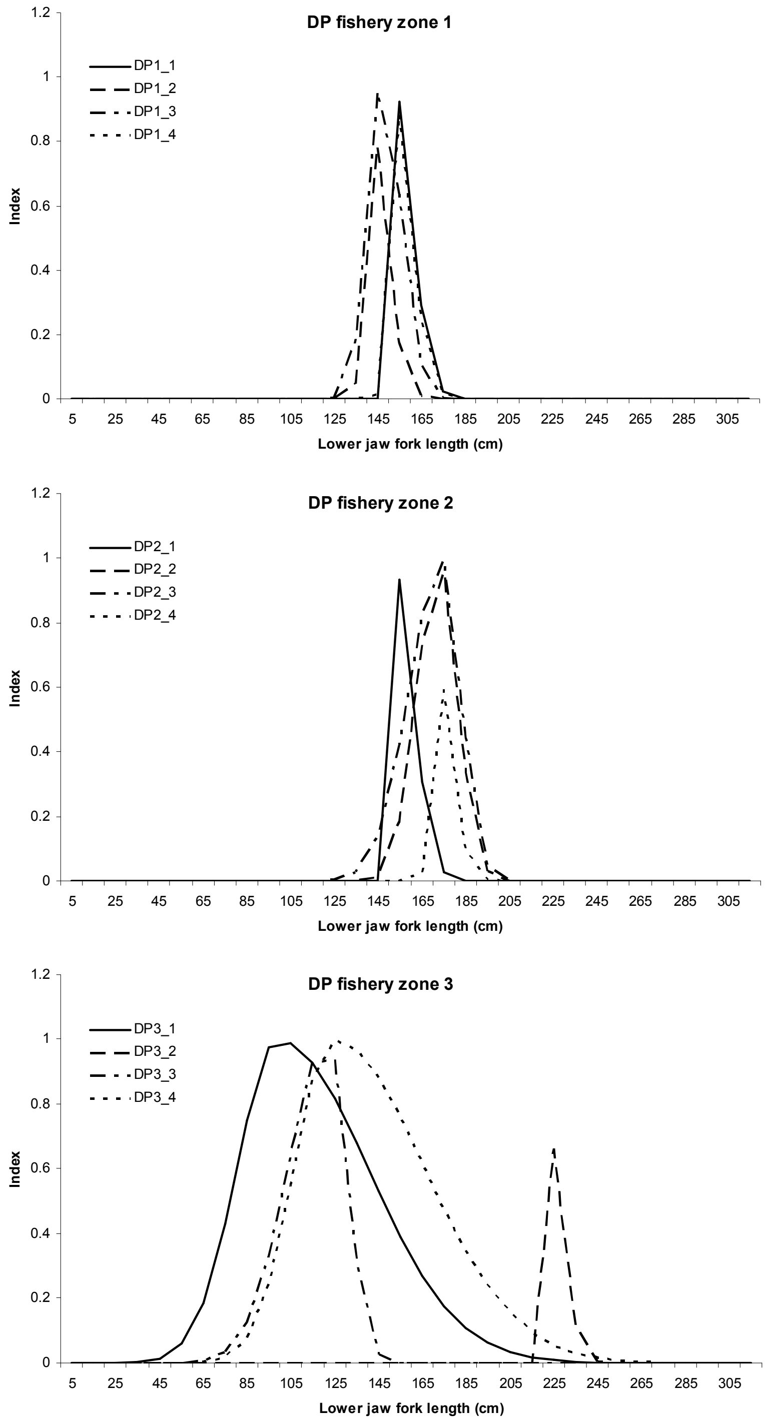


Figure 45: Example model (12211211) estimates of selectivity-at-length for the Distant water and Pacific Island (DP) fisheries in the northern, central and southern zones (1, 2, and 3) for each of the four quarters (_1 to _4).

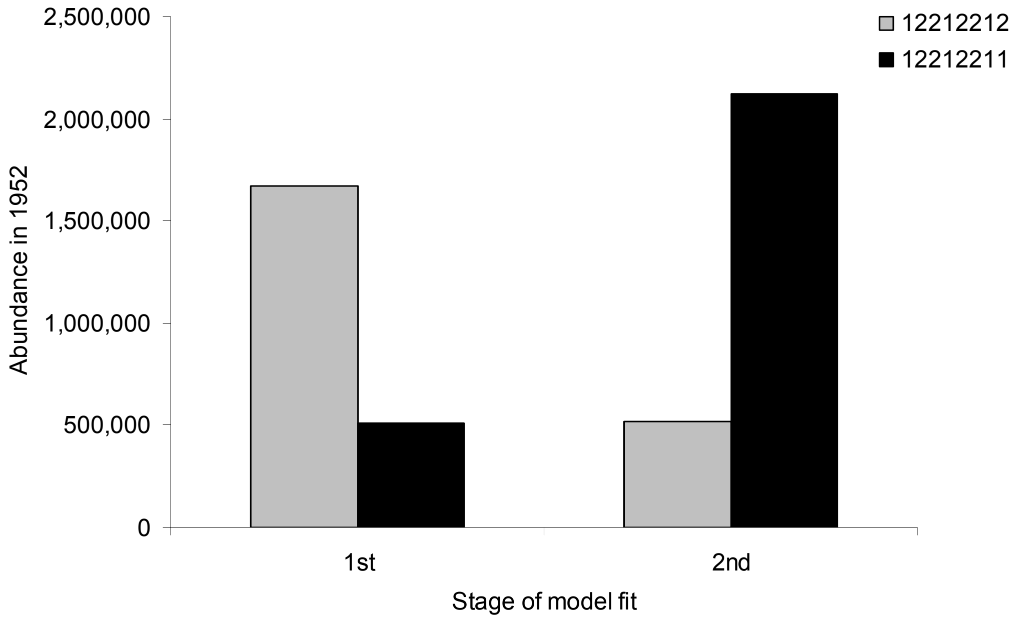


Figure 46: Model estimates of total abundance for two models (12212212, 12212211) differing only in respect of the uncertainty factor: fishery, showing the sensitivity to the initial parameter values used in fitting the model, where the fitted parameters from the first model fit (1^{st}) were switched between the models, and used as the initial parameter values for a second model fit (2^{nd}).

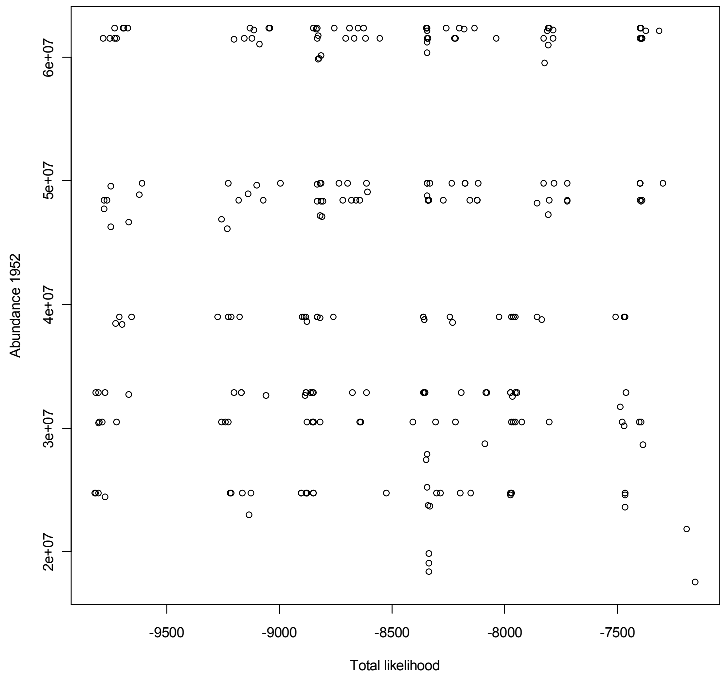


Figure 47: Scatterplot of the estimates total abundance in 1952 (no.s of fish) and the negative log-likelihood function for 256 models under the 4ar spatial option (areas 3 and 4).

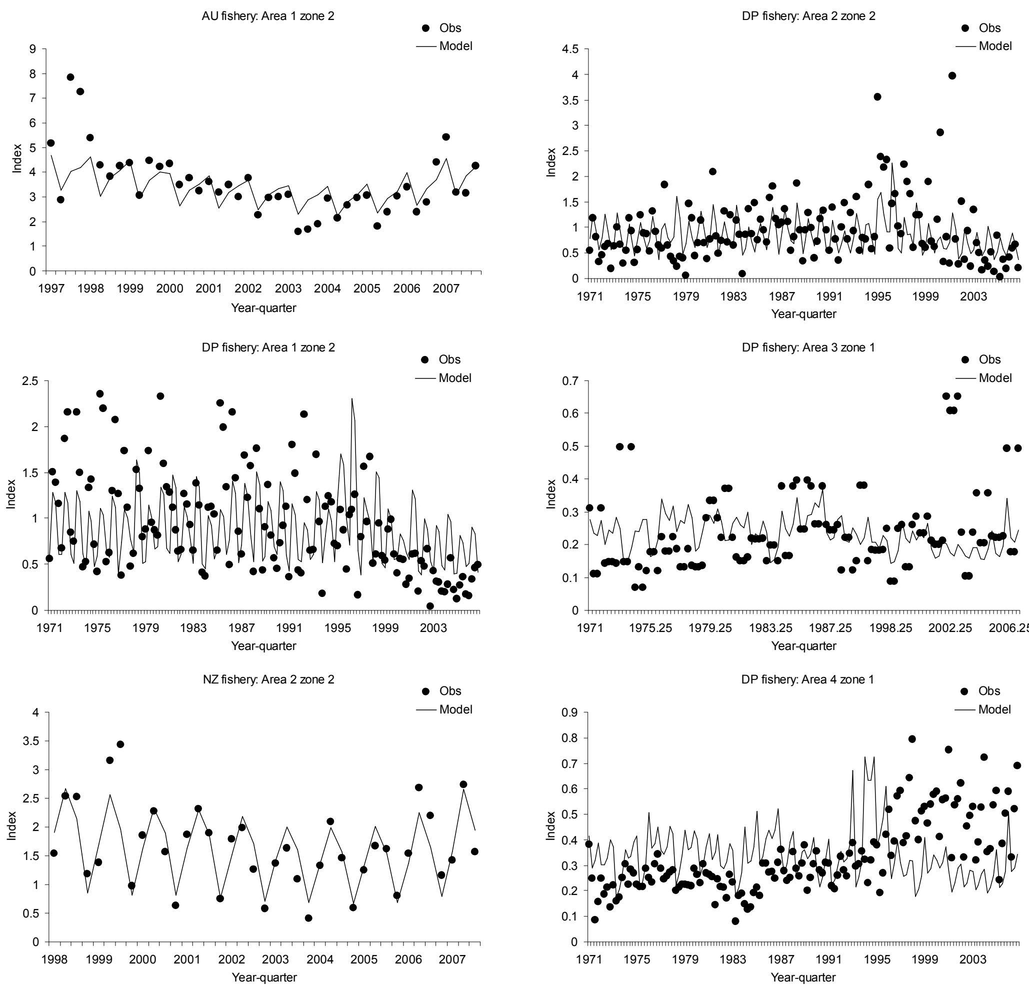


Figure 48: Swordfish CPUE for the AU, NZ, and DP fisheries in areas 1 to 4, zones 1 and 2 (spatial option 4ar) showing observed (Obs) and model (Model) values for an example model.