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**CASAL STOCK ASSESSMENT FOR SOUTH-WEST PACIFIC BROADBILL
SWORDFISH 1952-2004**

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Executive Summary

Swordfish catches in the south-west 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 1997 to 2003, regional swordfish catch was between 60 000 to 70 000 fish per year.

A swordfish population model for the south-west Pacific region has been developed using CASAL, and was fitted to catch-per-unit effort and catch-at-length observations collated from all the regional fisheries. The model runs investigated structural assumptions for either a single stock, or one that is spatially disaggregated with options for homogeneous mixing, mixing on shared spawning grounds, or for discrete spawning stocks with foraging site fidelity. Model sensitivity to certain of the structural and statistical assumptions was tested in terms of model quantities of management interest, such as the current stock status relative to recent historical levels. The CASAL model estimates were compared with the equivalent quantities derived from a parallel assessment model developed using Multifan-CL, fitted to the same set of observations, and sharing many of the structural and statistical assumptions.

While good fits were made to many of the observations, the CASAL model estimates of absolute stock size and current status were variable, such that the predicted impact of fishing and levels of depletion from virgin levels are uncertain. Estimates of current stock status from the more plausible model runs spanned the range of potentially overfished and underfished states. For example, model point estimates of current spawning stock biomass relative to the maximum unfished (virgin) stock size ranged from 37% to 77% for this set of models, and the estimated impact of fishing on spawning biomass ranged from 30% to 75% of the unfished population.

However, the model did provide more consistent predictions of the decline in spawning biomass since 1995 estimating a decline of 5% to 51% in spawning biomass since 1995. So while changes in absolute biomass are difficult to quantify, relative changes in abundance are more meaningful stock indicators from these models at this time.

When the CPUE data was given more weight relative to the catch-at-length observations, higher levels of depletion were estimated, but when the catch-at-length data was given relatively more weight, lesser levels of depletion were estimated. This example of data conflict is one example of some of the many problems encountered in this assessment. Model uncertainty is evident in its sensitivity to the structural and statistical assumptions made. Other sources of uncertainty include: estimation problems, particularly for migration parameters; implausible selectivity parameters that may alias for unrelated processes; and fleet-specific catchability coefficients that are counter intuitive. The full effects of the structural and statistical assumptions have not yet been fully explored in the model given the relatively narrow range of model options investigated. The largest uncertainty in the model related to estimates of

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absolute abundance, and, hence, the predicted relative fishing impact. There appears to be little information available in the observations from which to infer absolute levels of abundance.

It is recommended that the sources of model uncertainty be explored further with alternative processes for fleet-specific selectivities, catchabilities, and seasonal movement. The uncertainties identified in the model may provide a useful guide for future research using the models, or in establishing priorities for swordfish stock assessment projects such as tagging studies or large scale port sampling.

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). Spatially stratified catch rates in the Australian longline fishery indicate 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 and local management of fisheries impacting on swordfish populations may be warranted.

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 and the annual effort increased from around 2.8 million hooks to over 10 million hooks, 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 are currently less than 2000 t and 400 t in the Australian and New Zealand longline fisheries, respectively.

A number of fishery indicators have prompted concern for the status of swordfish in the south-west Pacific, including marked declines in catch-per-unit-effort and mean length of fish in catches. However, a regional stock assessment for swordfish has not yet been completed largely because of the limited availability of biological and fishery observations. An operating model of the south-west Pacific Ocean swordfish population has been developed and was conditioned on catch, effort and size data

from Japanese, Australian and New Zealand fisheries (Campbell & Dowling 2003). The dynamics of this model were highly uncertain, and this was attributed to a lack of information with which to estimate model parameters and, hence, stock status. Improving the amount and quality of available data was identified as a high priority. Consequently, the model was used for simulating population projections under a range of possible scenarios of current biomass. The projections were used to evaluate a range of management strategies that might underpin advice to fisheries managers.

Swordfish have been assessed elsewhere in the Pacific. A preliminary assessment for north Pacific Ocean swordfish was completed using MULTIFAN-CL (Kleiber & Yokawa 2002), and a framework has been prepared for extending this assessment to account for structural uncertainties (Sun et al. 2003). This assessment may assist in identifying the structural and process uncertainty to be taken account of in developing an assessment model for swordfish. A sex-specific age-structured assessment method for North Pacific swordfish was subsequently evaluated by simulation to identify the main sources of uncertainty (Wang et al. 2005). Process error in the relationship between CPUE and abundance was found to have the greatest impact on model performance, in terms of both bias and precision.

A swordfish population model for the south-west Pacific region has been developed using CASAL (C++ algorithmic stock assessment laboratory, Bull et al. 2005) and was fitted to catch-per-unit effort and catch-at-length observations collated from the Australian, New Zealand, Japanese and distant water fleets from other nations. The model runs we present investigate structural assumptions for either a single stock, or one that is spatially disaggregated with options for homogeneous mixing, mixing on shared spawning grounds, or for discrete spawning stocks with foraging site fidelity. We examine the sensitivity of model quantities such as the current stock status to the structural and statistical assumptions, . The CASAL model estimates are compared with the equivalent quantities derived from a parallel assessment model developed using MF-CL, fitted to the same set of observations, and sharing many assumptions.

Methods

Model specifications

The south-west Pacific swordfish abundance and yield were estimated using an age-structured population model with length-specific fishing mortality using the CASAL package which is described by Bull et al. (2005). 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. A brief description of the flexible framework for developing population models using CASAL is provided in Appendix 1.

A parallel stock assessment model has been developed for south-west Pacific swordfish by Kolody et al. (2006) using Multifan-CL (MF-CL) (Kleiber et al. 2003). To maintain comparability between the two models, where possible the specifications and assumptions made were kept similar. Kolody et al. (2006) investigated a wide range of models and the CASAL model replicates the assumptions made for example model 1. Details of the specification of this model are described by Kolody et al.

(2006). A brief outline of the specifications and assumptions made for the CASAL model equivalent follow, with the key differences between the two models identified.

There was insufficient information available from the regional population on sex composition to enable fitting a sex-structured assessment model that includes a female length-at-maturity ogive. Consequently, the model was not sexually disaggregated.

Spatial disaggregation
Both single and multiple area models were considered for the assessment. For the multiple area models, the spatial disaggregation assumed took account of two key processes: fish movement, and the distribution of fishing effort in nationally discrete fisheries.

An important assumption made in the model relates to the discreteness of the population and this determines the movement parameters to be defined, and hence the level of spatial disaggregation possible. Available information from which movement parameters may be inferred includes:
- cyclical patterns in CPUE indices in the marginal areas, viz., the Coral Sea, southeast Australia, and New Zealand. The seasonal catch rates in each region appear to be out of phase indicating north/south migrations; and,
- a seasonal cycle in the size distribution between areas that suggests seasonal movement of post-spawning fish offshore or north/south migrations.

These patterns indicate size-specific movement, however, an alternative that we have not modelled is that the pattern reflects sex-specific movement because females are typically larger than males.pattern reflects sex-specific movement because females are typically larger than males.

The spatial disaggregation of the model aims to also take account of consistencies in the seasonal and temporal trends in catch rates in parts of the region, and the spatial distribution of domestic longline fisheries. The fisheries themselves are defined such that each is a homogeneous unit having unique characteristics for selectivity and catchability that are time-invariant. Catch and effort information from the south-west Pacific regional fisheries were examined in detail in respect of homogeneity in catch rates and the spatial distribution of the fleets. The spatial distribution of catch rates indicated logical boundaries between areas, i.e., discrete areas having differing relative abundance. Therefore, areas were determined that generally represent relatively homogeneous units with respect to national fishing fleets as indicated by CPUE and effort (Kolody et al 2005).

To model processes underpinning the observed decline in CPUE in the Brisbane grounds, (implying residency or site fidelity), the east Australian waters were separated into inshore and offshore areas. Also, to take account of the size-specific differences in swordfish taken from the northern and southern areas of New Zealand, these areas were also separated.

The regional stock assessment model areas are shown in Figure 1, and are:
1   North-east Queensland, Coral Sea, PINs
2   Brisbane Grounds, Queensland - inshore

3	Brisbane Grounds, Queensland - offshore
4	New Zealand north
5	New Zealand south, south-east Australia, Tasmania
6	Eastern south Pacific

Areas 1 to 5 define the extent of the south-west Pacific stock. However, Area 6, that includes an area of high relative abundance in the north-eastern parts of the South Pacific, is defined for potential future developments of the stock assessment.

Fisheries
The fisheries operating in the south-west Pacific region have been defined by nationality, stratum, and catchability characteristics. Fleet structure was defined taking account of the typical fishing characteristics of each fleet, e.g. hooks per basket. These differences underpin assumptions regarding differences in fishing selectivity between the fleets. Three selectivities were used, defined by nationality as follows:
- Australia (AU);
- New Zealand (NZ), and
- Distant water fleets (DP) including the Japan fleet, distant water fleets mainly from Korea and Taiwan, and the Pacific Island Nations' fleet (PINs).

The combination of fleets and areas result in eleven discrete fisheries being defined (Table 1).

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 population was not allowed to fall to a level that gave a rate greater than 0.7.

Movement and migration
Two assumptions regarding fish movement between areas were made: homogeneous mixing; and foraging site fidelity (Figure 2).

i) Homogeneous mixing
This assumes the stock is a single homogeneous population with age-specific probabilities for seasonal migrations between adjacent areas. This may be a reasonable assumption given that there is currently no genetic evidence of sub-population structure within this region.

ii) Foraging site fidelity
Under this assumption the regional swordfish population was divided into five discrete stocks with each having site fidelity in its foraging, or home area. Area 2 was designated as being the spawning area. Sexually mature fish from Areas 1, 3, 4 and 5 migrate at the beginning of the fourth quarter to the spawning area. At the beginning of the first quarter all fish migrate back to their respective foraging areas without any mixing of fish between areas. The stock resident in Area 2 makes no migration. There appears to be sustained depletion in the Australian inshore fishing grounds as indicated by declining catch rates, while catch rates in other areas do not show this

decline. This suggests that the swordfish population does not redistribute amongst the areas.

A variation of this assumption was also considered which relaxed the area fidelity such that although fish make the spawning migrations, they mix in the spawning area and then may migrate to other foraging areas.

Population structure
The following assumptions were made regarding the population structure and biological parameters in the spatially aggregated and disaggregated models. These were based upon the findings of Young & Drake (2002, 2004), Griggs (2005), and Griggs et al. (2005).

Age classes:	0 to 20+ years; 20+ being an aggregate class
Stock-recruitment:	Beverton-Holt relationship; steepness 0.9
Age-at-maturity:	Logistic function with 50% maturity at age 10 years
Annual cycle:	Quarterly time steps
Initial start year:	1952
Recruitment:	One event per year at the beginning of quarter 1
Recruitment distribution:	Estimated for the spatially disaggregated models
Natural mortality:	A decreasing age-specific function that is constant, (Figure 3)
Growth:	von Bertalanffy parameters $k = 0.102$, $t_0 = -3.380$, $L_{inf} = 255.729$; with constant variation (cv = 0.10) around the predicted the mean length-at-age.

Length-weight:	parameters	a	b
	whole weight:	2.237e-5	2.896
	processed weight:	2.14e-5	2.902

Although length-weight parameters have been derived, the model is specified as being weightless, i.e., all calculations are made in respect of numbers of individual fish rather than as biomass and catch weights. This is because all catches and CPUE are expressed in terms of numbers of fish. However, the length-weight parameters are used to convert model estimates to biomass as required for certain output quantities.

Regional input data

Annual catches
Catch statistics from all fisheries operating in the south-west Pacific region are reported to the Western and Central Pacific Fisheries Commission (WCPFC), and are administered on their behalf by the Secretariat of the Pacific Community (SPC). Swordfish catch is reported as the frequency caught, i.e., numbers of fish caught per area and quarter.

The total catches by nation over all areas and for the core south-west Pacific areas (1 to 5) assumed in this assessment are presented in Figure 4, and the total catch in each area in Figure 5. Total annual catches in the core areas were relatively stable at around 25 000 to 30 000 swordfish. 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 50 000 in 2004.

Fishery CPUE
The years for which quarterly CPUE time series are available for each of the discrete fisheries are listed in Table 1. The main time series of standardised CPUE for the Japanese, distant water fleet, the Australian, and the New Zealand (Unwin et al. 2005) fisheries are plotted in Figure 6.

For the single area models, a single "global" CPUE time series was calculated using the combined standardised indices over all the fisheries (Figure 7). This weighted mean index took account of the relative size of each area and the ratio of the catchability coefficients for each fishery (Kolody et al. 2006).

Catch size compositions
A time series of catch-at-length observations is available for each fishery in the south-west Pacific region (Table 1), and the sizes of the samples for each fishery by nationality and area are presented in Figure 8. The large sample sizes for the Australian fleet collected in Areas 2 and 3 are 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.

Range of models

A range of model options was included for the assessment to investigate the effects of structural and statistical assumptions. The structural assumptions tested were the spatial disaggregation (five areas versus one area), and migration processes. The single area model was used to examine the effect of changing the weighting of the catch-at-length data. A list follows of the model run with an acronym and a description of the assumptions.

Model	Description
5ar_Fid	5 areas, 5 stocks, foraging site fidelity, spawning migrations,
5ar_Fid50	5 areas, 5 stocks, foraging site fidelity, spawning migrations, 50-fold down-weighting of catch-at-length likelihood term
5ar_NoFid	5 areas, 1 stock, no foraging site fidelity, spawning migrations with mixing between areas
5ar_Mix	5 areas, 1 stock, homogeneous mixing between areas
1ar_1CP	1 area, single stock, 10-fold down-weighting of catch-at-length likelihood term; fit to global CPUE
1ar_1CP50	1 area, single stock, 50-fold down-weighting of catch-at-length likelihood term; fit to global CPUE
1ar_1CP75	1 area, single stock, 75-fold down-weighting of catch-at-length likelihood term; fit to global CPUE
1ar_1CP100	1 area, single stock, 100-fold down-weighting of catch-at-length likelihood term; fit to global CPUE

No projections were carried out for assessing the impacts of future management.

Parameters estimated
Between 47 and 245 parameters were estimated depending upon the model assumptions (Table 2). These included selectivity parameters (3 for each fleet-specific selectivity function), migration parameters, year class strength (YCS) parameters, mean recruitment (R_0), and stock-recruitment relationship steepness.

i) Selectivity-at-length
Three separate size-based functions were estimated for the respective fleet nationalities: DP (Japanese, distant water fleets, and PINs), AU (Australia), and NZ (New Zealand). A double normal function was assumed, 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 number of swordfish recruiting at age 1 year to the population each year, and which would produce the virgin population size under zero fishing mortality. For the 5AR_Fid model option, five mean recruitments were estimated; one for each stock (area). The weak prior distribution assumed was uniform-log with lower and upper bounds of 10^3 and 10^7 respectively.

iii) Annual year class strengths (1969 – 2003)
The Haist parameterisation (Bull et al. 2005) was selected, which rescales all year class strengths to constrain mean YCS 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 1971 to enable the estimation of YCS for the period 1951 to 1968. Constant mean recruitment (R_0) was assumed for these years.

iv) Stock-recruitment relationship
The steepness parameter of the Beverton-Holt stock-recruitment relationship was estimated with a normal prior distribution, with a mean of 0.9 and c.v. = 0.2.

v) Recruitment distribution
For the 5AR_NoFid and 5AR_Mix model options the proportion of total recruitment to each area was estimated. For the 5AR_Fid model this was unnecessary because mean recruitment was estimated separately for each area (stock).

vi) Migration parameters
A three-parameter capped logistic function was estimated for each migration ogive, which determines the proportion of each age class that migrates. The parameters normal prior distributions were:

	a_{50}	a_{to95}	a_{max}

μ	9.0	3.0	0.2
cv	0.1	0.1	1.0

where a_{max} is the maximum proportion of fish migrating, a_{50} is the age at which the proportion is 50% of a_{max}, and the proportion is 95% of a_{max} at an age that is $a_{50}+a_{to95}$. For the 5AR_Fid model, spawning migrations were estimated, but it was assumed that all spawners return to the foraging grounds. For the 5AR_NoFid and 5AR_Mix model, migrations into and out of each area were estimated.

vii) Catchability
Catchability coefficients (q) were calculated analytically as nuisance parameters for each fishery for which there was an observed CPUE time series. Three fleet-specific, i.e., DP, AU, and NZ, catchabilities were calculated and were assumed to be constant across areas and seasons. This was based on a parsimonious assumption that the observed variations in catch rates amongst seasons and areas could be explained solely by migrations.

The fleet specific catchabilities were not scaled according to the relative effective area in each. This represents a significant difference from the MF-CL assessment model that included scalars for the relative effective area and a preferred ratio for the relativity of catchability between fleets and areas (Kolody et al. 2006). In attempting to replicate the similar catchability between the AU and NZ fleets implemented in MF-CL, a term was added to the objective function in CASAL that penalised the difference between the estimated catchabilities for these fleets.

Statistical assumptions
The mode of the Bayesian posterior distribution (MPD) was obtained to give point estimates of parameters for each model option from a maximum likelihood fit to the observations. Bayesian mean estimates were not calculated from an MCMC posterior distribution for logistical reasons.

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 0.2 over all years, and for the DP fisheries was 0.4 over all years. This reflects the view that the catch and effort reporting systems for the Australian and New Zealand fisheries are better administered. It was assumed the CPUE random variable was log-normally distributed. For the combined "global" CPUE time series a c.v. of 0.2 was assumed for all years.

The objective function term for the catch-at-length 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 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. For the five-area model options and the 1AR_1CP model option the catch-at-length data was down-weighted by a factor of 10 by multiplicatively down-scaling the sample sizes. For the 1AR_1CP50, 1AR_1CP75 and 1AR_1CP100 model options, this down-

scaling was increased to 50, 75 and 100 respectively. The sample sizes were thus decreased by these factors.

The individual likelihood terms making up the total objective function and the selected formulations are described by Bull et al. (2005). For each model option the standard deviations of the standardised residuals were examined. Values near 1.0 are considered consistent with the statistical assumptions and assumed variances.

Derived quantities

Model estimates were derived for quantities used to assess stock size and its relative status. These were:

B_0	- initial unfished (virgin) total stock biomass
B_{2004}, B_{1995}	- total stock biomass in 2004 and 1995
SSB_{2004}, SSB_{1995}	- spawning stock biomass in 2004 and 1995
TSB_{2004}/B_0	- total stock biomass in 2004 divided by (virgin) total stock biomass
TSB_{2004}/TSB_{1995}	- total stock biomass in 2004 relative to that in 1995
SSB_{2004}/SSB_{1995}	- spawning stock biomass in 2004 relative to that in 1995
$TSB_{2004}/TSB_{2004,NF}$	- total stock biomass in 2004 relative to that for an unfished population
$SSB_{2004}/SSB_{2004,NF}$	- spawning stock biomass in 2004 relative to that in for an unfished population
F_{2004}	- exploitation rate in 2004 (catch divided by start of year population in numbers of fish)
F_{2004}/F_{MSY}	- exploitation rate in 2004 divided by the rate for the maximum sustainable yield (in numbers of fish)

BMSY, the biomass that supports maximum sustainable yield was not available from the CASAL software for the swordfish model. Exploitation rate, F2004, could only be obtained in terms of numbers, not as a catch to biomass ratio.

Given the high uncertainty of the model estimates (described later) it was not considered useful to derive projection quantities.

Results

Model fits to observations

Only selected results of the model fits are presented to illustrate key aspects of the MPD point estimates, and the effects of structural and statistical assumptions on the fit to the observations.

Likelihood estimates
The catch-at-length terms are the largest component of the total likelihood (Table 3). The standard deviations of the CPUE normalised residuals are on average around 2.0, indicating that the assumed observation error c.v.s are too small for the model to be consistent with the data. The catch-at-length standard deviations are a good deal less than one for the down-scaled sample sizes, indicating that these effective sample sizes are too small for the model to be consistent with the data, i.e., the standard deviations are too high.

CPUE
Generally a good fit of the 5AR_Fid model was obtained to the CPUE time series for the AU fleet in Areas 2, 3 and 5 with the overall decline in catch rates reflected in the model estimates (Figures 9 to 11). The seasonality was reasonably well described by the model in Area 2, and the standardised residual diagnostics appeared satisfactory. Similarly, model estimates showed clear seasonality in Area 5 but under-estimated the peak catch rates in the second quarter causing a deviation from the assumptions of normality (see QQ-norm plot, Figure 11). The fit to the NZ fleet time series had inadequately large seasonal fluctuations, but an overall decline similar to that observed (Figure 12). CPUE for the AU fleet in Area 3 showed erratic, non-seasonal fluctuations that the model could not match, although the decline in average CPUE was reflected in the model estimates (Figure 10). The model indices were consistently lower than the observed estimates in this area, which may be indicative of the assumption that the fleet-specific catchability was constant over all areas. The model fit to the DP fleet CPUE observations in all areas was reasonable with the temporal trends in observed CPUE being predicted, but the fit to the high seasonality in Areas 2 to 5 was poor. The inability of the model to describe the seasonality in observed CPUE is reflected in the relatively high standard deviation of the standardised CPUE residuals (Table 3). Decreasing the relative weight of the catch-at-length term substantially improves the fit to the DP fleet CPUE and somewhat to the NZ series (Table 3).

The fits of the other spatially disaggregated models to the observed CPUE time series differed from that of model 5AR_Fid. The 5AR_NoFid performed poorly in describing the seasonality in CPUE, particularly in Areas 1, 3 and 4. For the model 5AR_Mix, although a good fit was achieved to the recent declines in average CPUE, no seasonality was evident in the model predictions.

The fundamental assumptions made in the single-area model 1AR_1CP regarding stock structure and movement, prevent the prediction of seasonality in the combined "global" CPUE time series (Figure 13). However, the underlying temporal patterns in average CPUE are reasonably well described by the model. In contrast, there is some seasonality in predicted CPUE indices for the single-area models with lower assumed relative weight assigned to the catch-at-length data, e.g., 1AR_1CP50 (Figure 13), despite the structural constraints of the model. This is likely to be an artefact attributable to unrelated parameters aliasing for within-year processes, such as seasonal movements, and is discussed later.

Catch-at-length
The fit of the 5AR_Fid model to the catch-at-length observations for AU fishery in Areas 2 and 3 was exceptionally good, (Figure 14, for example in quarter 2 and Area

2). This is reflected in the model estimation of the overall decline in mean length in catches from Area 2 and in all quarters since 1997 (Figure 15). Model predictions for the DP fishery catch-at-length were consistently smaller than observed in Area 5 (Figure 16), and this was also evident for the NZ fishery in that area. However, the numbers of observations for these fisheries were considerably smaller than for the AU fishery (Figure 8). The quality of fit to the AU series did not reduce with decreased relative weight of the catch-at-length time series for model 5AR_Fid50, however, the fit to the DP and NZ series became worse.

The model fit was improved somewhat for the NZ series in Area 4 in the 5AR_NoFid and 5AR_Mix models, with the right hand limb of the distribution being well described. This improvement is indicated by the likelihood estimate for this observation (Table 3). The overall fit of the 5AR_NoFid and 5AR_Mix models to the DP time series was similar to that of the 5AR_Fid model with a slight improvement for 5AR_Mix model (Table 3).

The 1AR_1CP model fit to the AU catch-at-length time series good with no consistent patterns in the standardised residuals, but a slight trend with respect to length for some areas. This might indicate some process error with respect the selectivity parameters. In all the single-area models, the fit to the NZ catch-at-length time series was poor, with the model under-estimating the catch-at-length on the right hand limb of the distributions producing high numbers of positive residuals. The single-area model fit to the DP series was relatively good in Areas 1 to 4, but not in Area 5 where fish sizes were underestimated. This quality of fit deteriorated under lower assumed relative weight for these observations, (models 1AR_1CP50 to 1AR_1CP100), producing consistent patterns in the standardised Pearson residuals with respect to length for most areas.

Model parameters

Year class strengths
YCS estimates for the 5AR_Fid model are variable over the 5 areas (Figure 17) and are not normally distributed. The mean YCS since 1993 is 66% and 49% of the average value for Areas 2 and 4, respectively. This decline is most likely to be related to the model predicted CPUE decline in the AU and NZ fisheries in those areas. A similar pattern in YCS is evident for the years 1993 to 2003 in almost all models, with weak YCS in 1999 and 2002. This was evident in Areas 2 and 3 in the 5AR_Fid model estimates. These patterns are also evident in the single-area models; however, increasingly frequent near zero recruitments were estimated for models with lower relative weight assumed for the catch-at-length observations (Figure 17).

Selectivity-at-length
Selectivity-at-length estimates, particularly for the AU and NZ fisheries, were sensitive to the different structural assumptions made in the five-area models (Figure 18). The estimated NZ function ranged from being dome-shaped for the 5AR_NoFid model to be selective either for small or large fish in the 5AR_Fid or 5AR_Mix models respectively. The AU function was either dome-shaped or selective for large fish. The estimated DP function was consistently dome-shaped, and was strongly selective for large fish under the 5AR_Mix model (Figure 18).

Selectivity-at-length estimates, particularly for the DP and NZ fisheries, were sensitive to the different statistical assumptions made in the single-area models (Figure 19). As the relative weight of the catch-at-length observation were decreased in the model fit, selectivity estimates for the NZ and DP fleets became increasingly implausible with the DP selectivity function reduced to a sharp "spike", and the NZ function suggesting selectivity for implausibly small fish (Figure 19). The AU function appears to be robust to this assumption and is dome-shaped with a maximum at around 165 cm.

Migration ogives
A high maximum spawning migration fraction was estimated for the 5AR_Fid model from Area 5 to the spawning area (Figure 20). Also this ogive differs from the estimated age-at-maturity function determined for swordfish where 50% sexual maturity occurs at around 10 years of age. The spawning migrations predicted at lower ages and the high proportion migrating reflects the level of seasonal movement required to fit the high seasonality in CPUE in Area 5, and to some extent in Area 4, that is evident in the DP and AU fishery time series. The relatively low level of spawning migration predicted for Area 3 is consistent with the minimal seasonality evident in model catch rate estimates in that area.

Migration appears to have been poorly estimated in the other spatially disaggregated models. For the 5AR_NoFid model the spawning and foraging migrations were extremely different for a given area, with near-zero migrations estimated in Areas 1, 3, and 4, and 100% spawning migration in Area 5. These are implausible and result in certain areas functioning as population sources or sinks. For the 5AR_Mix model, migration parameters were not able to be estimated, with most parameters not altering from their initial values despite convergence being achieved in the minimisation. This result is evident in the CPUE fits for this model where no seasonal variation in catch rates was described. With this structure it is typically difficult or impossible to estimate both migration and selectivity ogives.

Catchability coefficients
For the spatially disaggregated models the catchability coefficients for the AU and NZ fleets that were constrained to be similar, had estimated ratios near 1.0 (Table 4), which is consistent with the assumption made in the MF-CL model. However, the ratios for the AU and NZ fleet catchabilities to that of the DP fleet were lower than that assumed for the MF-CL model by factors of between 2 and 5 in the case of the 5AR_Fid and 5AR_Fid50 models.

Population biomass
Estimates of mean recruitment and hence absolute abundance, expressed in tonnes, are highly variable between the model options (Table 5 and Figure 21). For the spatially disaggregated model options, initial unfished biomass estimates (B_0) range from 47 to 140 kt with current biomass between 14 and 109 kt. For the single-area models initial unfished biomass estimates (B0) range from 38 to 590 kt with current biomass between 12 and 528 kt. A substantially smaller population size is estimated for the single-area models that assume lower relative weight for the catch-at-length observations. This is also evident for the spatially disaggregated model 5AR_Fid50

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(Figure 21). Spatially disaggregated models where the assumption for discrete populations is relaxed also estimate smaller population abundance.

All the model options estimate a decline in abundance with the rate increasing after 1994 (Figure 21). Those models estimating lower population abundance (5AR_NoFid, 5AR_Mix, and single-area models with low catch-at-length relative weight) indicate a greater decline from the unfished population size, compared with the 5AR_Fid and 1AR_1CP models. The former set of models estimate a decline to between 30% and 60% of the total unfished stock biomass in 2004, while for the 5AR_Fid and 5AR_Fid50 models the decline is less, 70% to 80% of the unfished biomass in 2004 (Table 5). The estimated range for the effect of fishing on spawning stock biomass is wide; to between 10% and 75% of the unfished biomass for these models (Figure 21).

Over all the model options, the total stock biomass was estimated to decline from 1995 to 2004 to between 53% and 85% of what it was, and for the spawning stock biomass the decline was to between 60% and 95%. The range for current stock size relative to the maximum unfished (virgin) stock size was from 37% to 77% for the most plausible models (Table 5).

Estimated total abundance in the areas of the 5AR_Fid model was variable but the general trends were similar, with large declines since 1992 in all areas except Area 1 (Figure 22). The result for the 5AR_Fid50 model was similar. Around 75% of the stock biomass was estimated on average to be in Areas 2, 3 and 4. For the 5AR_NoFid and 5AR_Mix models the area-specific total biomass estimates were implausible for some areas because of the poor performance in estimating migration parameters.

Discussion

Uncertainty in the parameter estimates
Although a relatively narrow range of point estimates were considered using the CASAL model, the results reveal that all the independent parameters estimated are sensitive to the statistical and structural assumptions. For the single area models the AU selectivity estimates were relatively robust to the statistical assumptions tested, and this is most likely attributable to the large effective sample size of these observations and the consistency of the time series. However, the AU and NZ selectivity estimates were sensitive to assumptions in the spatially disaggregated models. The DP and NZ selectivity estimates were highly sensitive to assumptions in the single-area models.

Both the absolute values of the fleet-specific catchability coefficients and their ratios between fleets were sensitive to assumptions, with some estimates being implausible. For example, the DP tuna by-catch and AU swordfish target fisheries were estimated to have similar catchabilities in the 5AR_Fid50 model. For some fisheries the quality of the CPUE fits were compromised by the assumption that fleet-specific catchabilities were constant across areas. For example, the model fit to the AU series for Area 3 reflected the overall decline in CPUE, but the modelled indices were

consistently negatively biased. The assumption of fleet-specific catchability being constant across areas was relaxed in the MF-CL model.

All the models predicted either below average or declining trends in YCS since 1993 and this achieved fits to the declines in observed CPUE in the AU, NZ and DP fisheries in Areas 2, 3 and 4. These low YCS estimates were also consistent with the AU fleet catch-at-length observations. YCS estimates were highly variable between areas in the 5AR_Fid model (having discrete populations), and achieved excellent fits to the catch-at-length observations in most areas and for most fleets. The models where fewer YCSs were estimated were sensitive to the assumptions. Inconsistencies in the data are discussed below.

Of the spatially disaggregated models, apart from that assuming foraging site fidelity, the migration parameters appear to have been poorly estimated; being either implausible (resulting in population sources and sinks in particular areas), or optimal migration solutions not being obtained. This is of concern given that the spatially disaggregated models all appear to fit the seasonal CPUE fluctuations in the AU fishery in Area 2 reasonably well despite the differences in the migration estimates and the assumptions made for movement processes. Alternative inferences regarding migration are equally well supported by the CPUE observations.

Data conflict
The results suggest conflict between the CPUE and catch-at-length data. The relative weighting of the catch-at-length observations influences mean recruitment, such that smaller population size with a larger decline is estimated for models that assume lower relative weight for the catch-at-length observations, and conversely. The effect appears to be similar for either the spatially disaggregated model (assuming foraging site fidelity), or the aggregated (single-area) models. This results in uncertainty in the model estimates of current stock status.

The effect of increased down-weighting of the catch-at-length data in single area models is an improved fit to the within-year seasonality in CPUE. Since these model assumptions exclude processes for seasonal variation in availability, it is likely that the improvement in fit is an artefact. This is clear since the estimates of selectivity-at-length for the NZ and DP fleets appear implausible, with the DP function reduced to a single "spike", the NZ function only selective for small fish, and a high frequency of near-zero YCS estimates. Combinations of values of these parameters produce predicted CPUE that emulates the seasonal variation in the observed CPUE in some years.

For the spatially disaggregated model option 5AR_Fid, the effect of increased down-weighting of the catch-at-length data clearly improved the fit to the seasonal variation in CPUE for fisheries in the Areas 1, 4 and 5. As with the single-area models, the selectivity functions were sensitive to this assumption, with the NZ and DP functions being less plausible. The failure of the 5AR_Fid model to describe CPUE seasonality in some fisheries may be a consequence of other factors affecting observed CPUE besides swordfish availability, such as spatial-temporal patterns in catchability or selectivity caused by changing fishing practices. The effects of some of these factors should have already been accounted for in the CPUE standardisation (Unwin et al. 2005). Another possible contributing factor to the lack of fit to the seasonality in

CPUE for the five-area models is the assumption regarding the spawning migrations. These were specified to occur only in the fourth quarter, and relaxation of this assumption may improve the model performance.

The apparent data conflict does not appear to affect the model predictions of relative population abundance in recent years. Model estimates of recent stock declines are similar, and consistently good fits were achieved to the CPUE and catch-at-length time series from the AU fishery in Area 2, indicating the simultaneous decline in mean length and catch rates. However, the high sample size in the AU fishery catch-at-length time series relative to the other fisheries is likely to have contributed to the consistent quality of the model fit, and the inferences and AU selectivity-at-length estimates were mostly robust to the assumptions tested as a result.

Uncertainty due to structural assumptions
The model estimates were sensitive to the assumptions made regarding stock structure and movement. For the spatially disaggregated models that allow population mixing between areas, smaller absolute population sizes were estimated with larger declines compared to those with discrete populations with the foraging site fidelity assumption. The effects of the structural assumptions for a single-area model were confounded with those of the statistical assumptions. The single-area model 1AR_1CP estimates of absolute abundance appear to be implausibly high, nearly six-fold higher than those of other models. Yet single-area models with lower relative weighting of the catch-at-length data consistently predicted lower abundance than the spatially disaggregated models 5AR_Fid, 5AR_Fid50, and 5AR_NoFid, with only the 5AR_Mix model predicting a similarly low stock size.

The structural assumptions for spatial disaggregation and foraging site fidelity appear to have improved the model fit to the observations, particularly in Areas 2 and 5, with apparently plausible migration parameters estimated. The high migration proportion estimated for Area 5 appears consistent with the general understanding of swordfish movement . Detailed examination with nested models may determine if this improvement is significant given the increased number of free parameters.

In summary, the CASAL models all described the general observed temporal trends well and achieved good fits to the long term patterns in the CPUE time series. Differences related mostly to parameters that could improve the fits to the seasonal variations in catch rates. This feature was consistent over all the models considered and was evident also in the predicted relative decline in total stock abundance by 2004 to between 53% and 85% of the levels in 1995. Highest uncertainty in the model related to estimates of absolute abundance and hence of the total decline since fishing began. There appears to be little information in the observations from which to determine stock structure and the appropriate weighting for the catch at length data is unclear. The most meaningful stock indicators from the model are those for recent relative change in stock size.

There are a number of differences in the structural and statistical assumptions made in the MF-CL and CASAL models that prevent direct comparisons between the estimates. CASAL differs from MF-CL as follows:
-        no relative effective area scalars on catchabilities were applied, and catchability was assumed constant (no temporal variation);

- CPUE is fitted as an abundance index;
- fleet-specific selectivity-at-length were assumed constant for all areas;
- YCS was constrained to have a mean = 1.0; and,
- different observation error assumptions

Given the range of uncertainties identified in the CASAL model, the underlying sources of the differences between it and the MF-CL estimates are not clear. One difference is the catchability assumption made in the MF-CL model that allows for spatial differences in fleet-specific catchabilities, and the relative effective area catchability scalars in the spatially disaggregated model. This entails differences in the interpretation of area-specific CPUE, or standardised effort that is likely to produce differences in estimates of area-specific abundance.

Despite these differences, the CASAL estimates for a number of the model options, fall within the range of those predicted by the MF-CL model. For example, CASAL models predict the relative decline in total stock abundance by 2004 is to between 53% and 85% of the levels in 1995, while the range for MF-CL is 56% to 74%. Also the CASAL models predict the impact of fishing on the total stock biomass relative to that if no fishing had occurred to be to around 30% to 80% of the unfished level. The range for the MF-CL model is 31% to 69%.

The full effects of the structural and statistical assumptions have not yet been fully explored in the CASAL model given the relatively narrow range of model options investigated. Given the limited range of model options considered and the wide uncertainty in the estimates, no clear statements regarding stock status may be made. It is recommended that the sources of model uncertainty must be explored further with alternative processes being considered for fleet-specific selectivities and catchabilities, and for seasonal movement. A useful aim would be to determine the main source of uncertainty in deriving estimates of mean recruitment, and, hence, total population abundance. The uncertainties identified in the model may provide a useful guide for future research using the models, or in establishing priorities for swordfish stock assessment projects such as tagging studies or large scale port sampling. For example, the model fit to the AU fishery catch-at-length data illustrated was clearly consistent with the observed simultaneous decline in CPUE in that area. This consistency most likely reduced uncertainty in the model estimates of relative abundance, and prompts a recommendation for larger collections of catch-at-length data for swordfish. This is supported by the view of Wang et al. (2005) that process error in the relationship between CPUE and abundance was found to have the greatest impact on model performance for north Pacific swordfish, in terms of both bias and precision. This effect could be offset through increasing the sample size of length-frequency information, particularly where there are several sources of uncertainty in fitting the assessment model.

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Figure 22: Total stock biomass in each area of the five stock model including foraging site fidelity (5AR_Fid).

Table 1: The discrete fisheries defined for the regional stock assessment models for south-west Pacific swordfish, with the available CPUE and catch-at-length time series for each. Note, the start and end years do not indicate that all intervening years or seasons of catch-at-length are necessarily available.

Fishery label	Area	Description	Selectivity ogive	CPUE	Catch-at-length
1	1	Japanese + distant water fleets + PIN	DP	1971-2004 (qtrs 1-4)	1971-2004 (qtrs 1-4)
2	2	Japanese + distant water fleets + PIN	DP	1971-2004 (qtrs 1-4)	1971-2004 (qtrs 1-4)
3	3	Japanese + distant water fleets + PIN	DP	1971-2004 (qtrs 1-4)	1971-2004 (qtrs 1-4)
4	4	Japanese + distant water fleets	DP	1971-2004 (qtrs 1-4)	1972-2004 (qtrs 1-4)
5	5	Japanese + distant water fleets	DP	1971-2004 (qtrs 1-4)	1991-2003 (qtrs 1-3)
7	2	Australian domestic	AU	1997-2004 (qtrs 1-4)	1997-2004 (qtrs 1-4)
8	3	Australian domestic	AU	1997-2004 (qtrs 1-4)	1998-2004 (qtrs 1-4)
9	5	Australian domestic	AU	1997-2004 (qtrs 1-4)	1997-2004 (qtrs 1-4)
10	4	NZ domestic domestic	NZ	1993-2004 (qtrs 1-4)	1994-2004 (qtrs 1-4)
11	5	NZ domestic	NZ	none	1996-2004 (qtrs 2-3)

Table 2: Independent parameters estimated in the CASAL models for south-west Pacific region swordfish, including migration, selectivity, catchability, year class strengths (YCS), mean recruitment (R_0), and stock-recruitment relationship steepness.

Model	Migration	Selectivity	Catchability	YCS	R_0	Steepness	Total params
5ar_Fid	12	9	3	159	5	5	193
5ar_Fid50	12	9	3	159	5	5	193
5ar_NoFid	28	9	3	35	1	1	77
5ar_Mix	196	9	3	35	1	1	245
1ar_1CP		9	1	35	1	1	47
1ar_1CP50		9	1	35	1	1	47
1ar_1CP75		9	1	35	1	1	47
1ar_1CP100		9	1	35	1	1	47

Table 3:   Maximum likelihood estimates for the CASAL swordfish model with the components for catch-at-length (cal) and CPUE terms for the DP, AU and NZ fleets, and the standard deviation of the standardised residuals for the CPUE likelihood terms (normalised residuals) and catch-at-length likelihood terms (Pearson residuals), for each national fleet, where the CPUE term for the single-area models is the global CPUE time series (DP cpue*).

Model	DP_cal	AU_cal	NZ_cal	TOT_cal	DP_cpue	AU_cpue	NZ_cpue	TOT_cpue	Total
5ar_Fid	-13900.3	-4370.7	-2135.5	-20406.5	304.1	-11.3	44.2	337.1	-20069.4
5ar_Fid50	-15246.3	-4720.3	-2343.6	-22310.3	178.2	-3.5	20.7	195.5	-22114.8
5ar_NoFid	-13801.9	-4386.2	-2164.1	-20352.2	326.8	62.7	103.6	493.1	-19859.0
5ar_Mix	-13980.8	-4325.5	-2179.2	-20485.5	488.4	152.6	94.9	735.9	-19749.6
1ar_1CP	-13780.5	-4281.4	-2170.7	-20232.6	194.6*	-	-	-	-20232.6
1ar_1CP50	-15166.7	-4653.0	-2339.2	-22158.9	49.7*	-	-	-	-22158.9
1ar_1CP75	-15373.7	-4680.9	-2406.1	-22460.6	35.9*	-	-	-	-22460.6
1ar_1CP100	-15497.8	-4715.9	-2448.1	-22661.9	34.5*	-	-	-	-22661.9

Model	sd(DP_cal)	sd(AU_cal)	sd(NZ_cal)	sd(TOT_cal)	sd(DP_cpue)	sd(AU_cpue)	sd(NZ_cpue)	sd(TOT_cpue)
5ar_Fid	0.86	0.79	0.65	0.83	1.69	1.80	2.58	1.74
5ar_Fid50	0.46	0.42	0.51	0.46	1.57	1.86	2.21	1.63
5ar_NoFid	0.96	0.79	0.77	0.91	1.72	2.23	3.32	1.86
5ar_Mix	0.76	0.75	0.34	0.73	1.86	2.68	3.22	2.03
1ar_1CP	0.93	0.84	0.70	0.89	2.48	-	-	-
1ar_1CP50	0.46	0.47	0.57	0.48	2.00	-	-	-
1ar_1CP75	0.39	0.49	0.54	0.43	1.95	-	-	-
1ar_1CP100	0.34	0.50	0.49	0.40	1.94	-	-	-

Table 4:   CASAL model estimates for catchability coefficients that are constant for each national fishing fleet (AU, DP, and NZ) over all areas, with the relative ratios between fleets.

Model	NZ	AU	DP	AU:NZ	NZ:DP	AU:DP
5ar_Fid	0.0012744	0.0012770	0.0008015	1.00	1.59	1.59
5ar_Fid50	0.0021077	0.0020239	0.0028310	0.96	0.74	0.71
5ar_NoFid	0.0041405	0.0040902	0.0015090	0.99	2.74	2.71
5ar_Mix	0.0037697	0.0038755	0.0028888	1.03	1.30	1.34
1ar_1CP			0.0000006			
1ar_1CP50			0.0000123			
1ar_1CP75			0.0000261			
1ar_1CP100			0.0000319			

Table 5: CASAL model estimates of recruitment, stock abundance and status: mean recruitment (R_0), initial unfished total stock biomass (B_0), total and spawning stock biomass in 2004 and 1995 (TSB_{2004}, TSB_{1995}, SSB_{2004}, SSB_{1995}), total stock biomass in 2004 divided by (virgin) total stock biomass (TSB_{2004}/B_0), total and spawning stock biomass in 2004 relative to that in 1995 (TSB_{2004}/TSB_{1995}, SSB_{2004}/SSB_{1995}), total and spawning stock biomass in 2004 relative to that in for an unfished population ($TSB_{2004}/TSB_{2004,NF}$, $SSB_{2004}/SSB_{2004,NF}$), exploitation rate in 2004 in respect of numbers of fish in the population (F_{2004}), and in relation to the exploitation rate for the maximum sustainable yield (F_{2004}/F_{MSY}). All biomass is ×1000 t.

Model	R_0 ('000)	B_0	B_{2004}	B_{1995}	SSB_{2004}	SSB_{1995}	TSB_{2004}/TSB_{1995}
5ar_Fid	593.96	140.47	108.71	130.09	67.01	71.99	0.77
5ar_Fid50	473.62	112.01	80.33	102.80	50.98	55.34	0.72
5ar_NoFid	370.09	87.54	54.16	70.35	31.45	38.30	0.62
5ar_Mix	198.74	47.00	14.29	25.65	3.03	6.23	0.30
1ar_1CP	2493.90	589.81	528.47	624.37	357.60	376.14	0.90
1ar_1CP50	321.52	76.04	46.74	63.99	28.16	32.71	0.61
1ar_1CP75	183.40	43.38	15.97	27.77	8.09	12.05	0.37
1ar_1CP100	162.42	38.41	11.60	21.93	5.28	8.85	0.30

Model	TSB_{2004}/TSB_{1995}	SSB_{2004}/SSB_{1995}	$TSB_{2004}/TSB_{2004,NF}$	$SSB_{2004}/SSB_{2004,NF}$	F_{2004}	F_{2004}/F_{MSY}
5ar_Fid	0.84	0.93	0.78	0.75	0.023	0.23
5ar_Fid50	0.78	0.92	0.73	0.71	0.032	0.35
5ar_NoFid	0.77	0.82	0.63	0.58	0.042	0.22
5ar_Mix	0.56	0.49	0.29	0.10	0.101	0.79
1ar_1CP	0.85	0.95	0.94	0.94	0.006	0.05
1ar_1CP50	0.73	0.86	0.62	0.58	0.051	0.51
1ar_1CP75	0.58	0.67	0.36	0.30	0.118	1.00
1ar_1CP100	0.53	0.60	0.29	0.22	0.147	n.a.
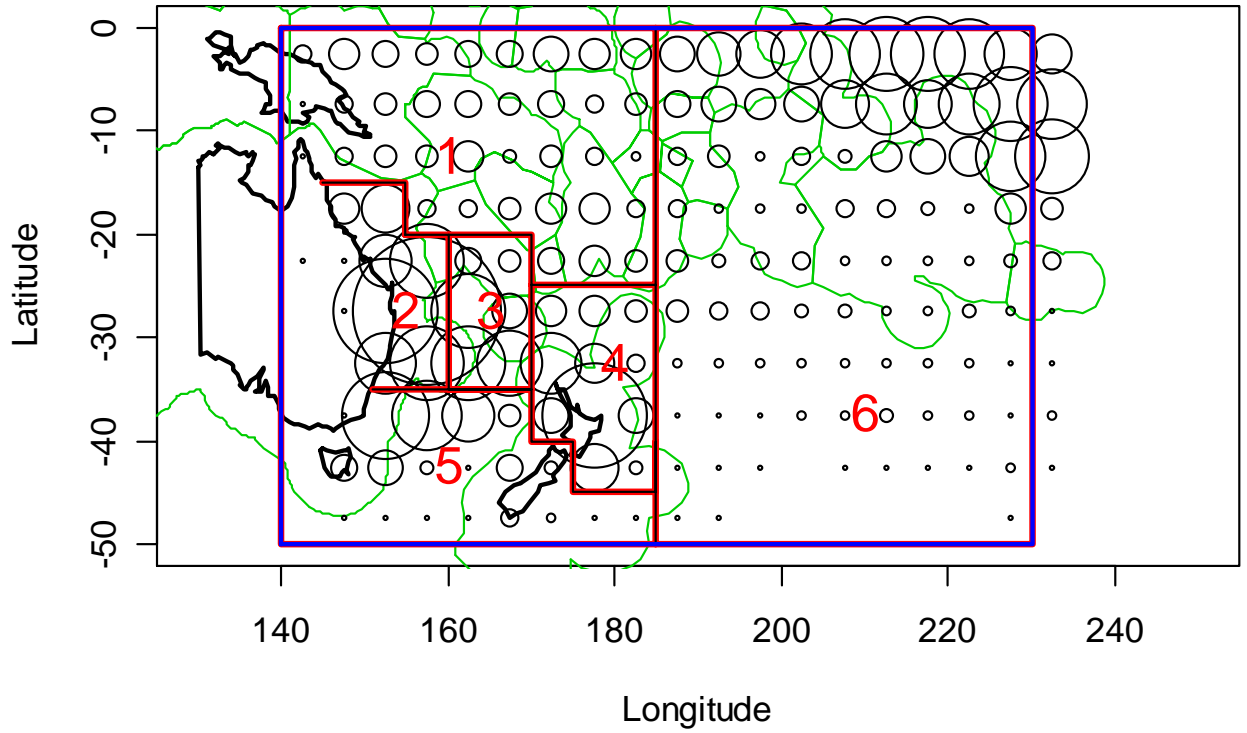
Figure 1: Spatial disaggregation of the south-west Pacific region assumed for the swordfish regional stock assessment model. Circles indicate the relative catch in 5°×5° squares over all fleets from 1952 to 2004. (Figure taken from Kolody et al. 2006)
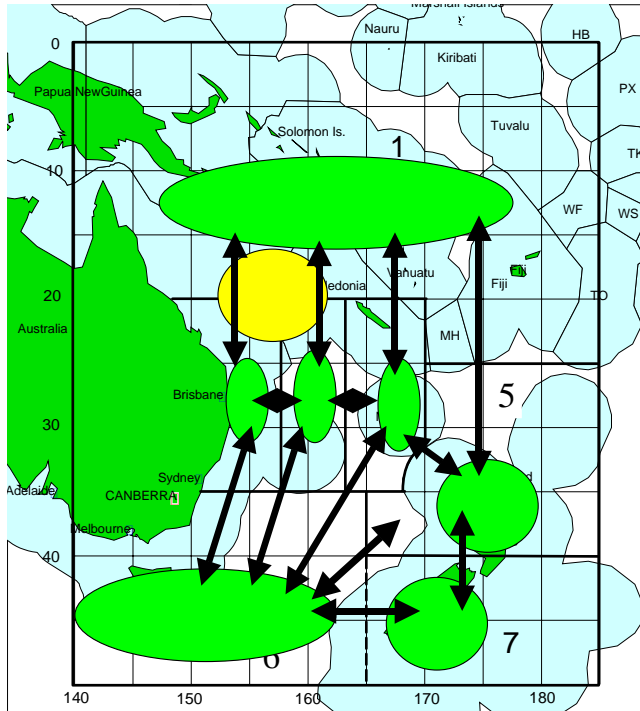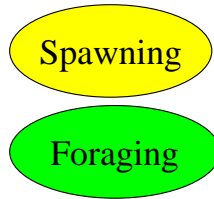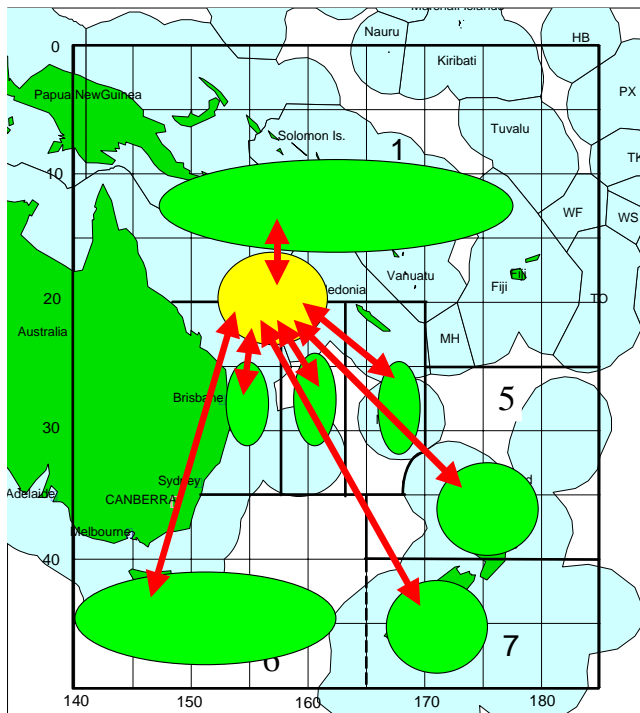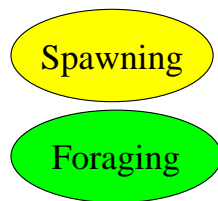
Figure 2: Alternative population movement hypotheses for swordfish assumed in the model for the south-west Pacific region. (Figure taken from Kolody et al. 2006. Note: areas shown are not as defined for the CASAL model)
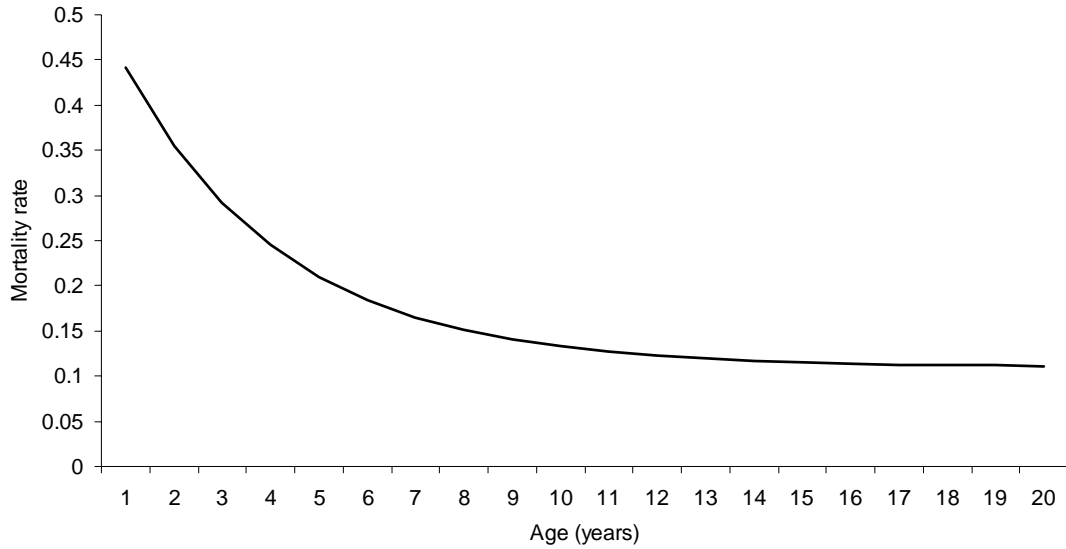
Figure 3:   Age-specific natural mortality
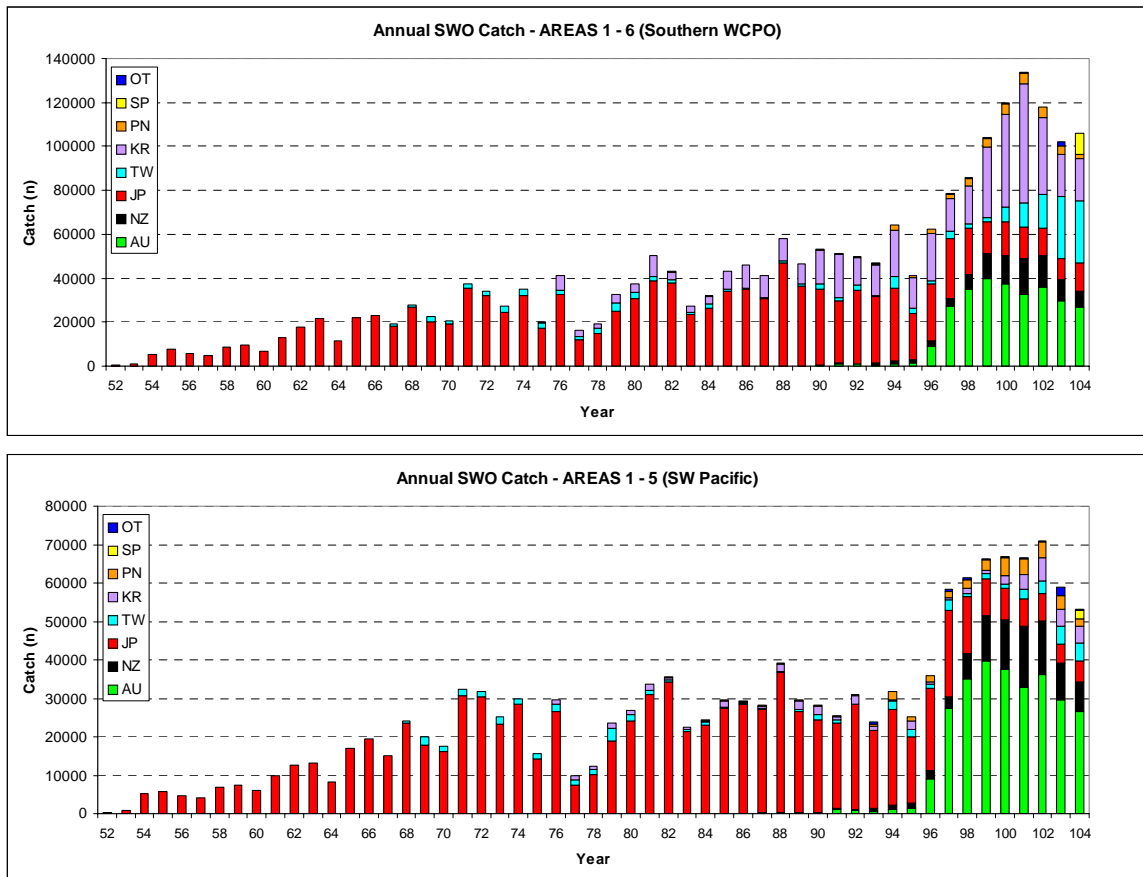
Figure 4:   The total catch by nation over all areas in the south-west Pacific region
and for the core assessment Areas 1 to 5, from 1952 to 2004 (52 – 104).
Nations are denoted: OT – other, SP – Spain, PN – Pacific Island nations,
KR – Korea, TW – Taiwain, JP – Japan, NZ – New Zealand, AU –
Australia.
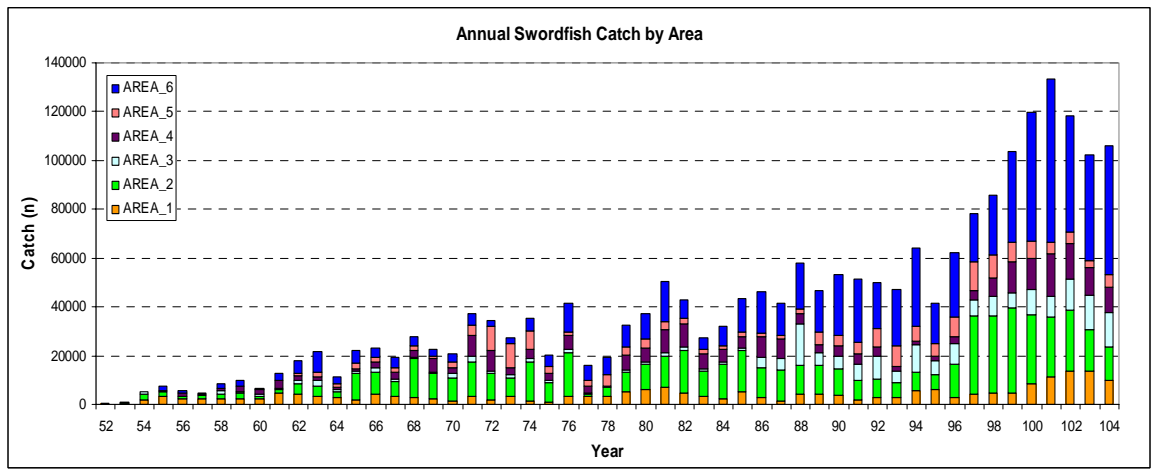
Figure 5: The total catch by area in the south-west Pacific region, from 1952 to 2004 (52 – 104).
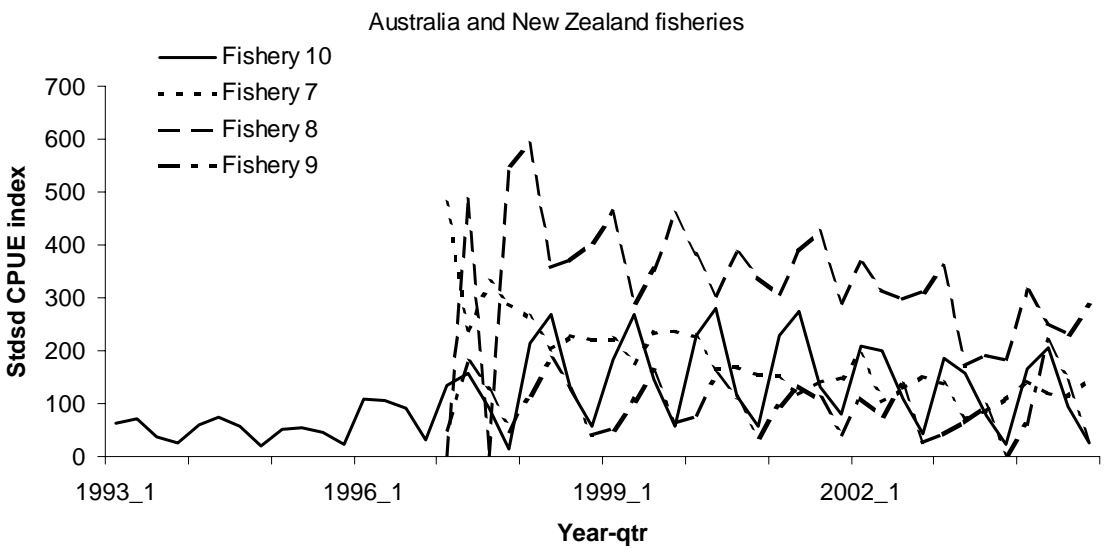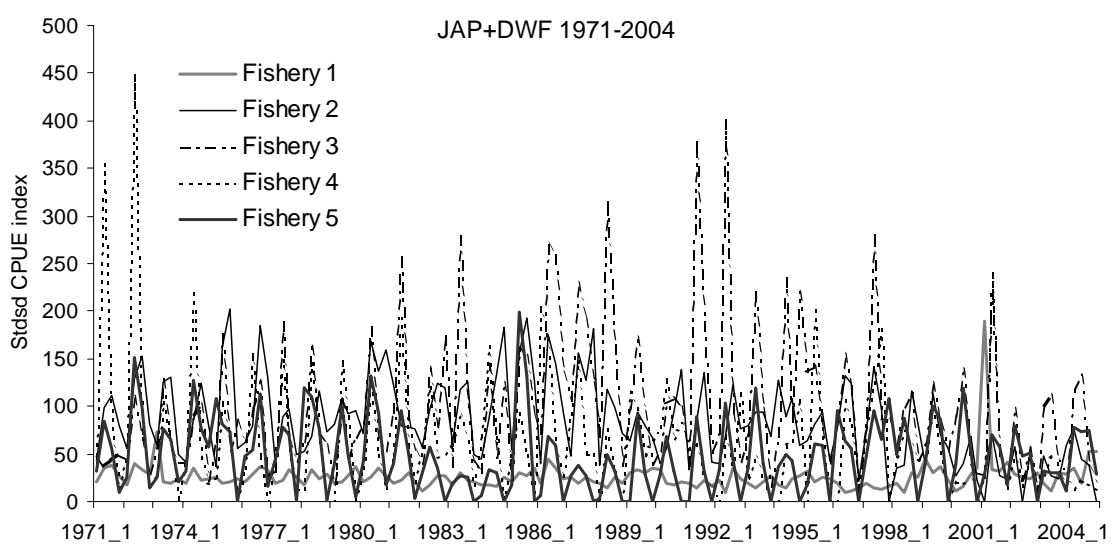
Figure 6: Standardised (Stdsd) CPUE indices for the combined Japanese, distant water, and PINs fishery, and the Australian and New Zealand fisheries.
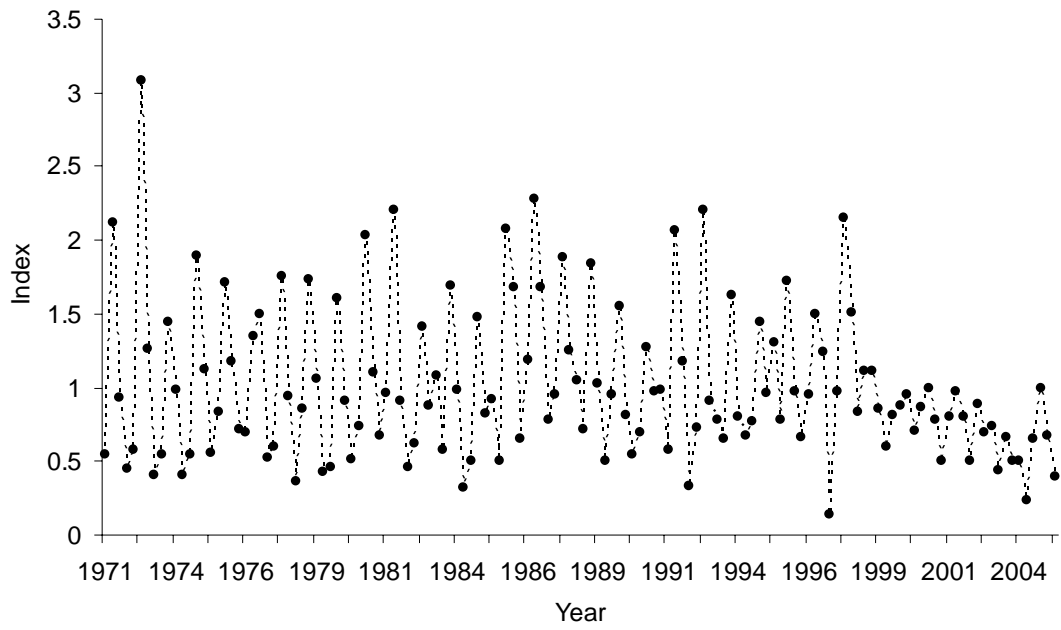
Figure 7: CPUE indices for all fisheries combined over the south-west Pacific region.
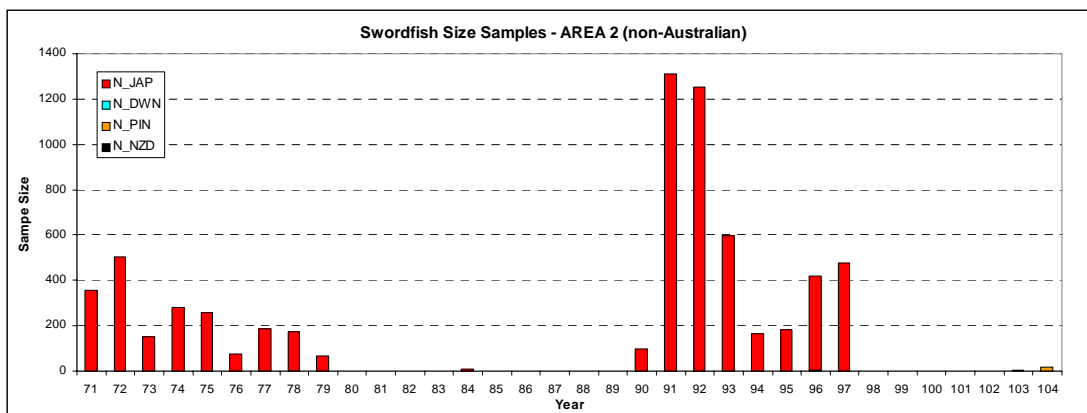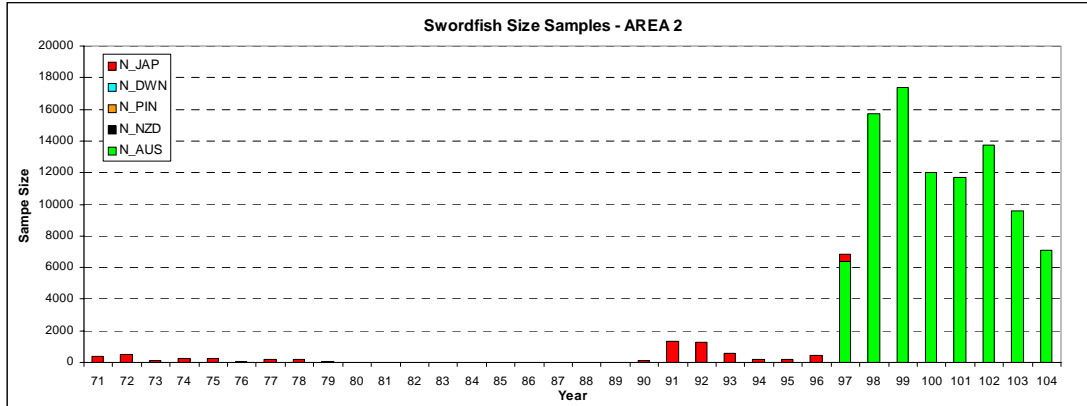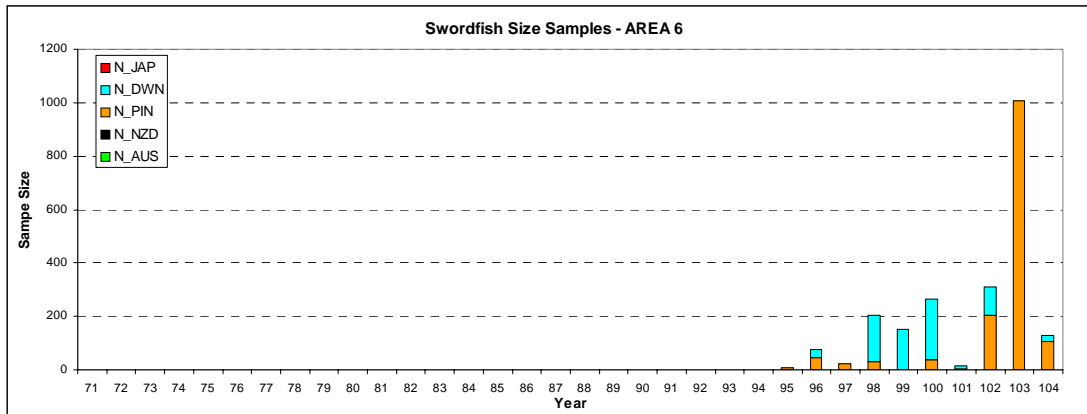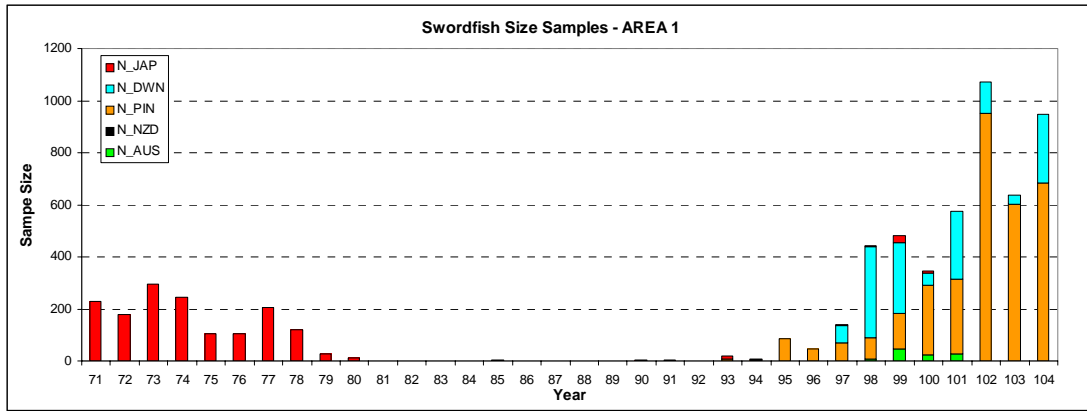
Figure 8:   Swordfish catch-at-length sample sizes for Areas 1 to 6 by fishing
nationality, 1952-2004 (52 – 104).

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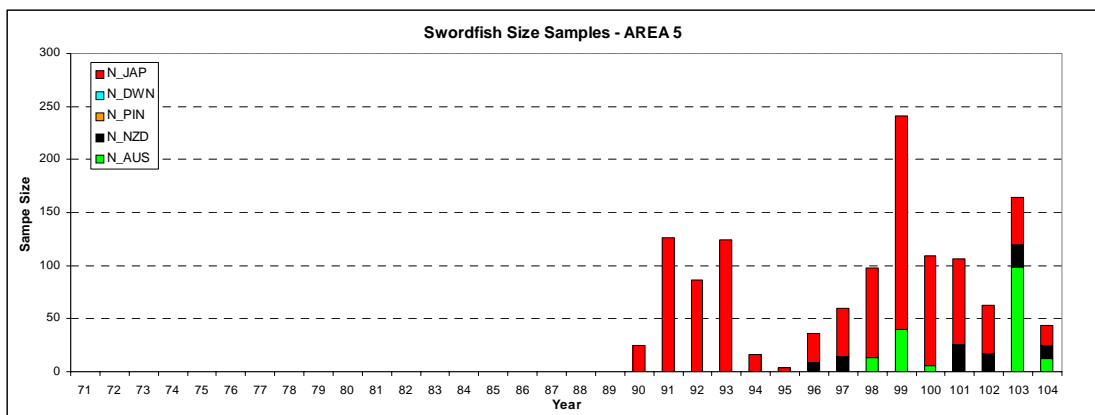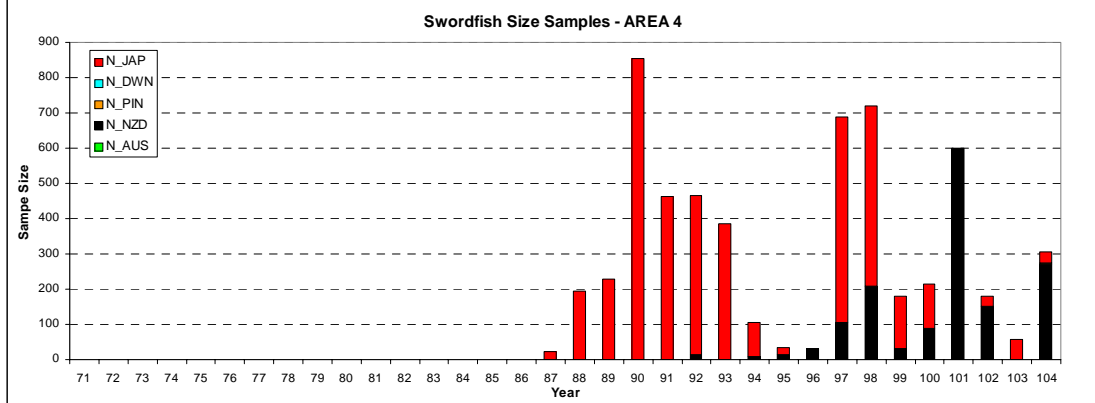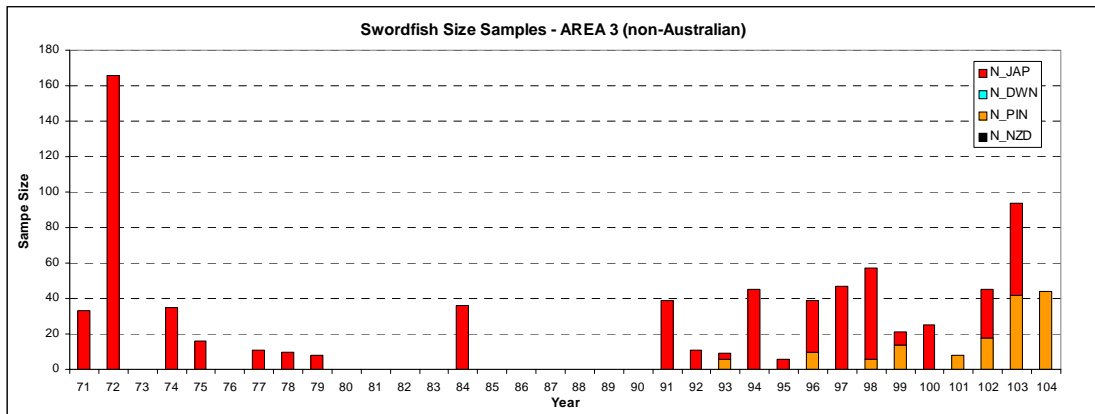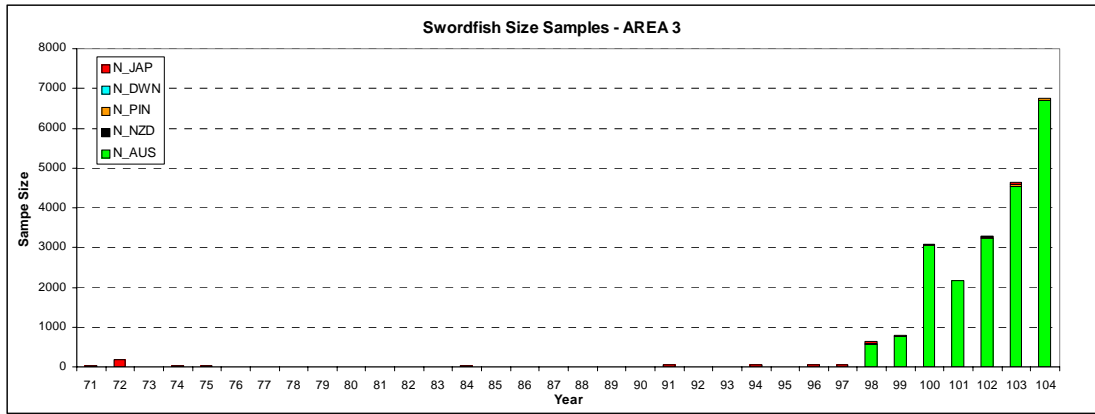
Figure 8 cont.
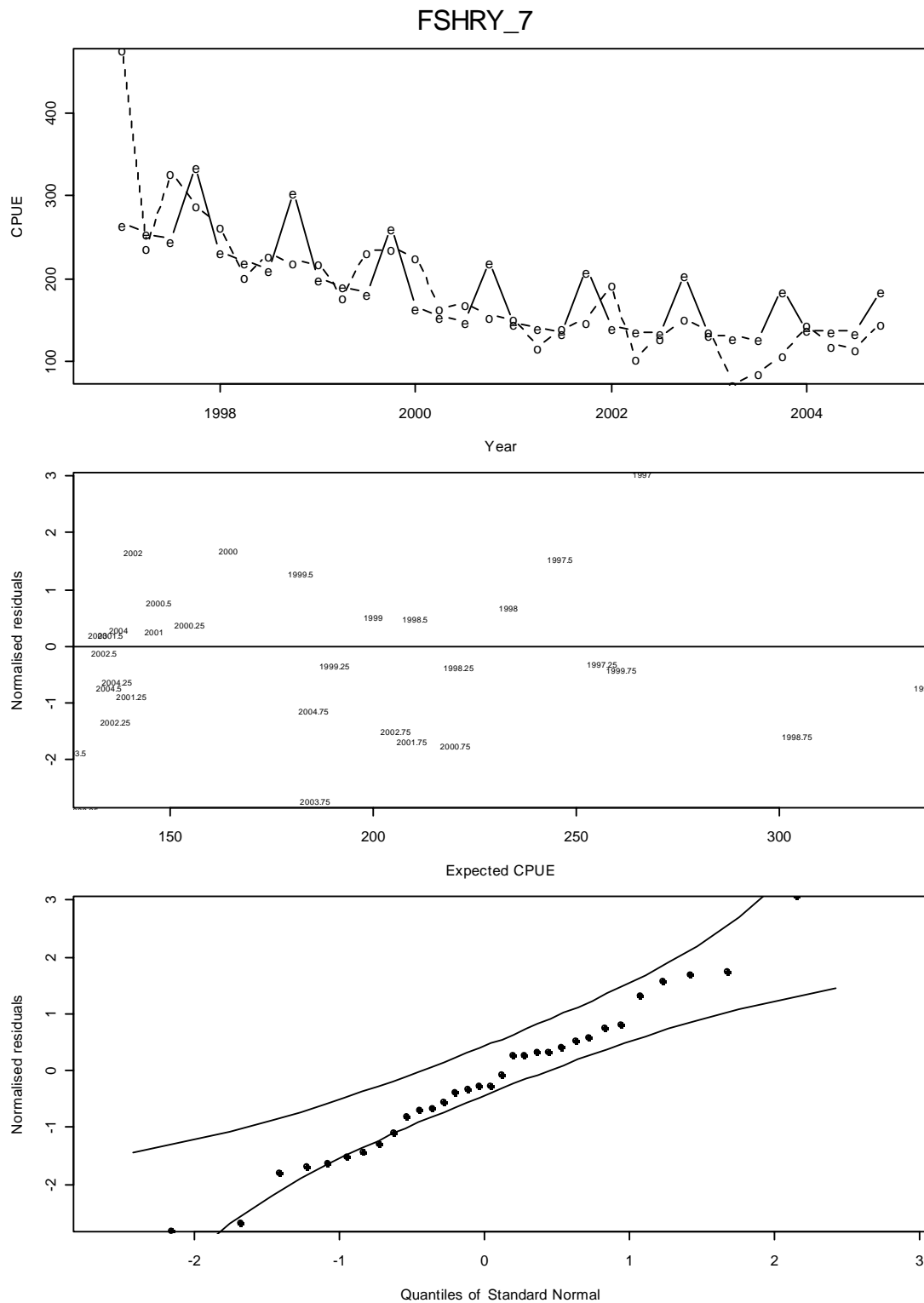
Figure 9:   Swordfish CPUE for the AU tuna longline fishery in Area 2 (top panel) showing observed (-o-) and fitted (-e-) values for the five-area model including foraging site fidelity (5AR_Fid), with diagnostic plots of the normalised residuals (bottom two panels).
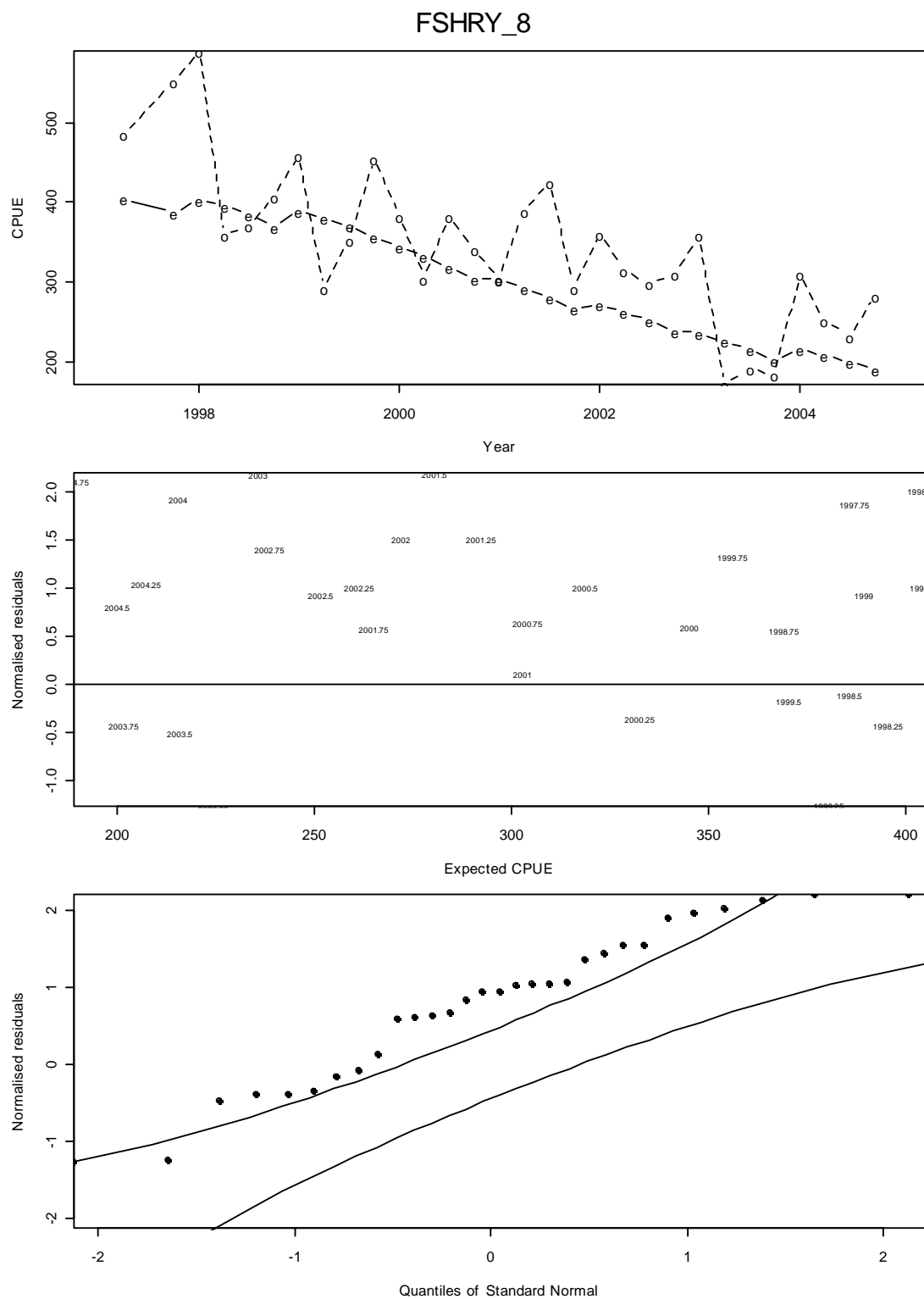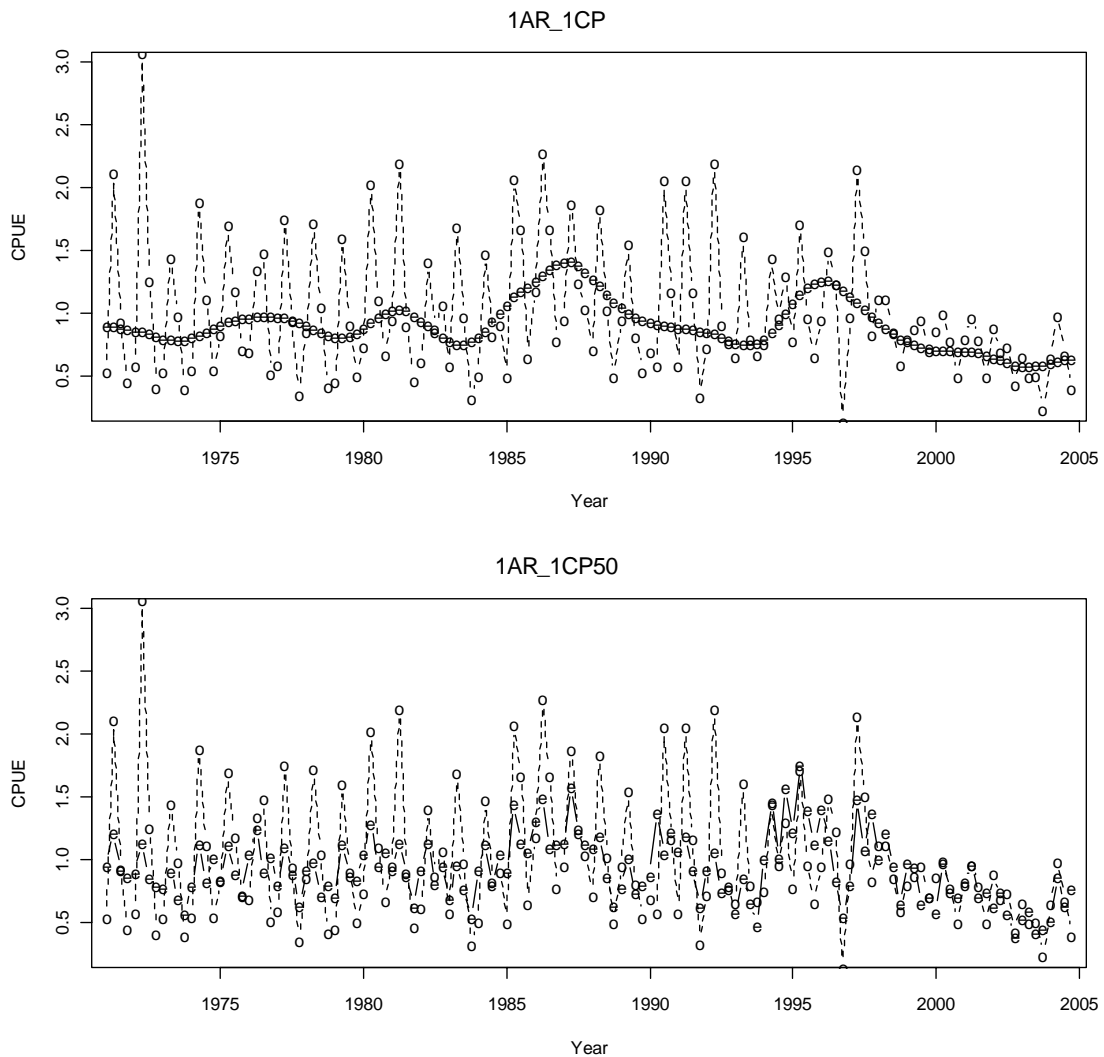
Figure 10: Swordfish CPUE for the AU tuna longline fishery in Area 3 (top panel) showing observed (-o-) and fitted (-e-) values for the five-area model including foraging site fidelity (5AR_Fid), with diagnostic plots of the normalised residuals (bottom two panels).

FSHRY_9
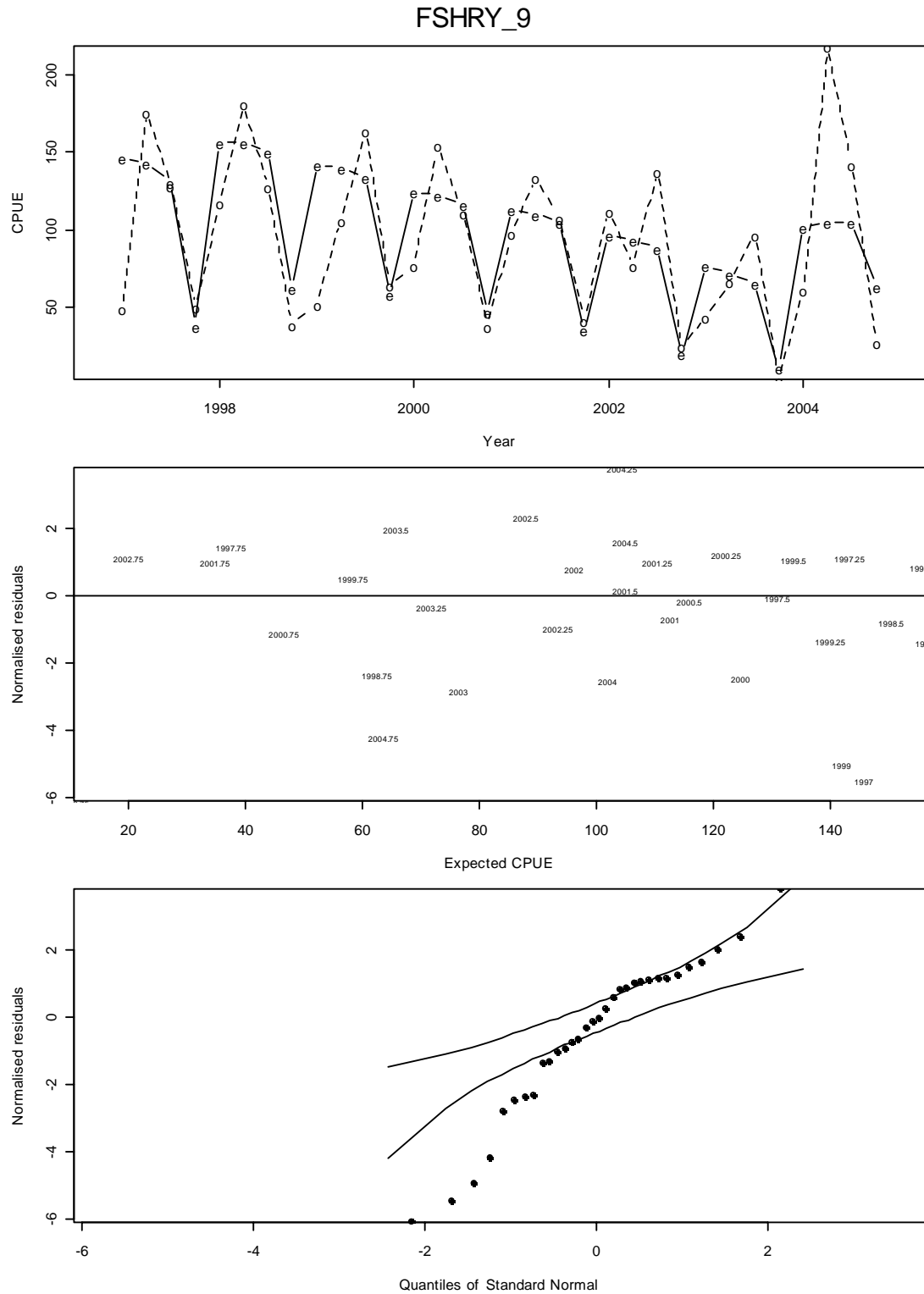
Figure 11: Swordfish CPUE for the AU tuna longline fishery in Area 5 (top panel) showing observed (-o-) and fitted (-e-) values for th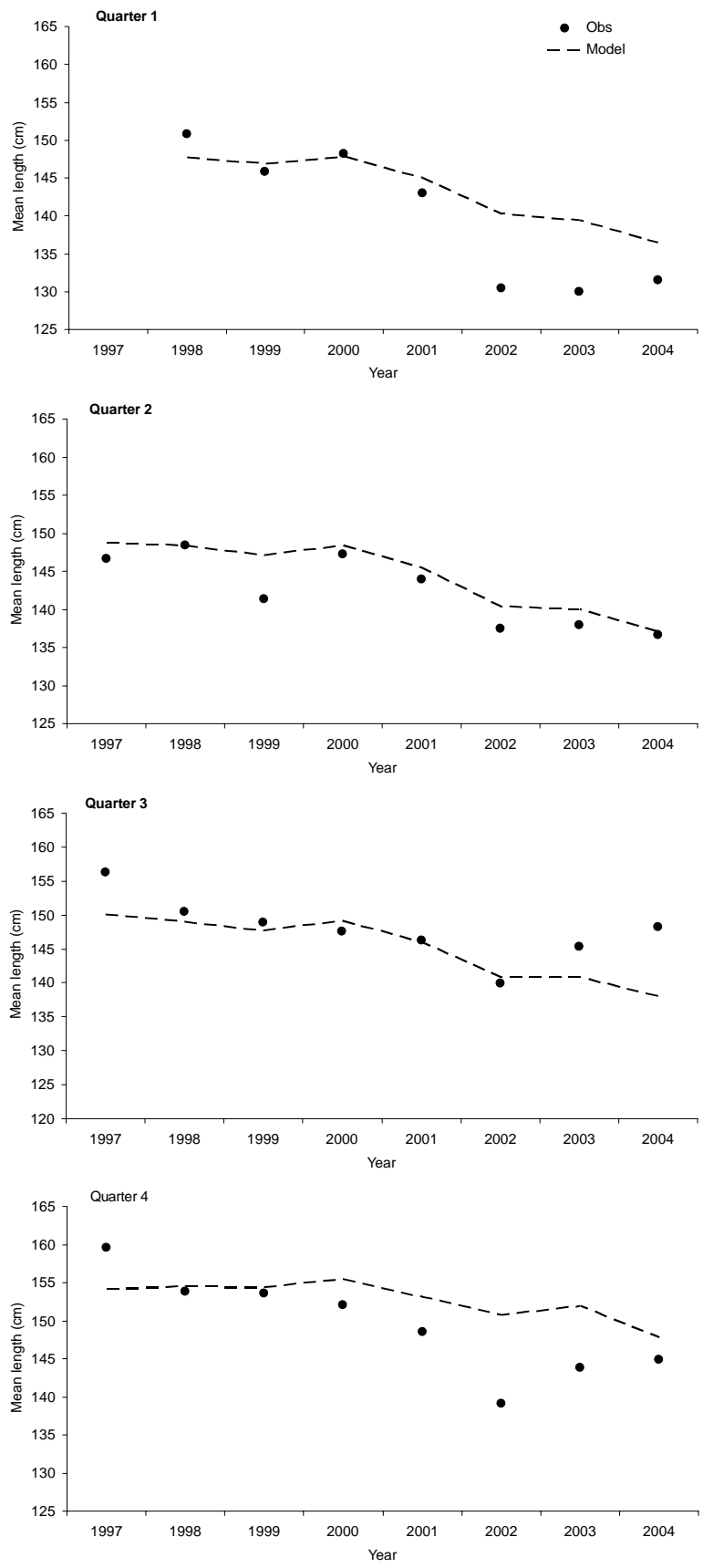e five-area model including foraging site fidelity (5AR_Fid), with diagnostic plots of the normalised residuals (bottom two panels).
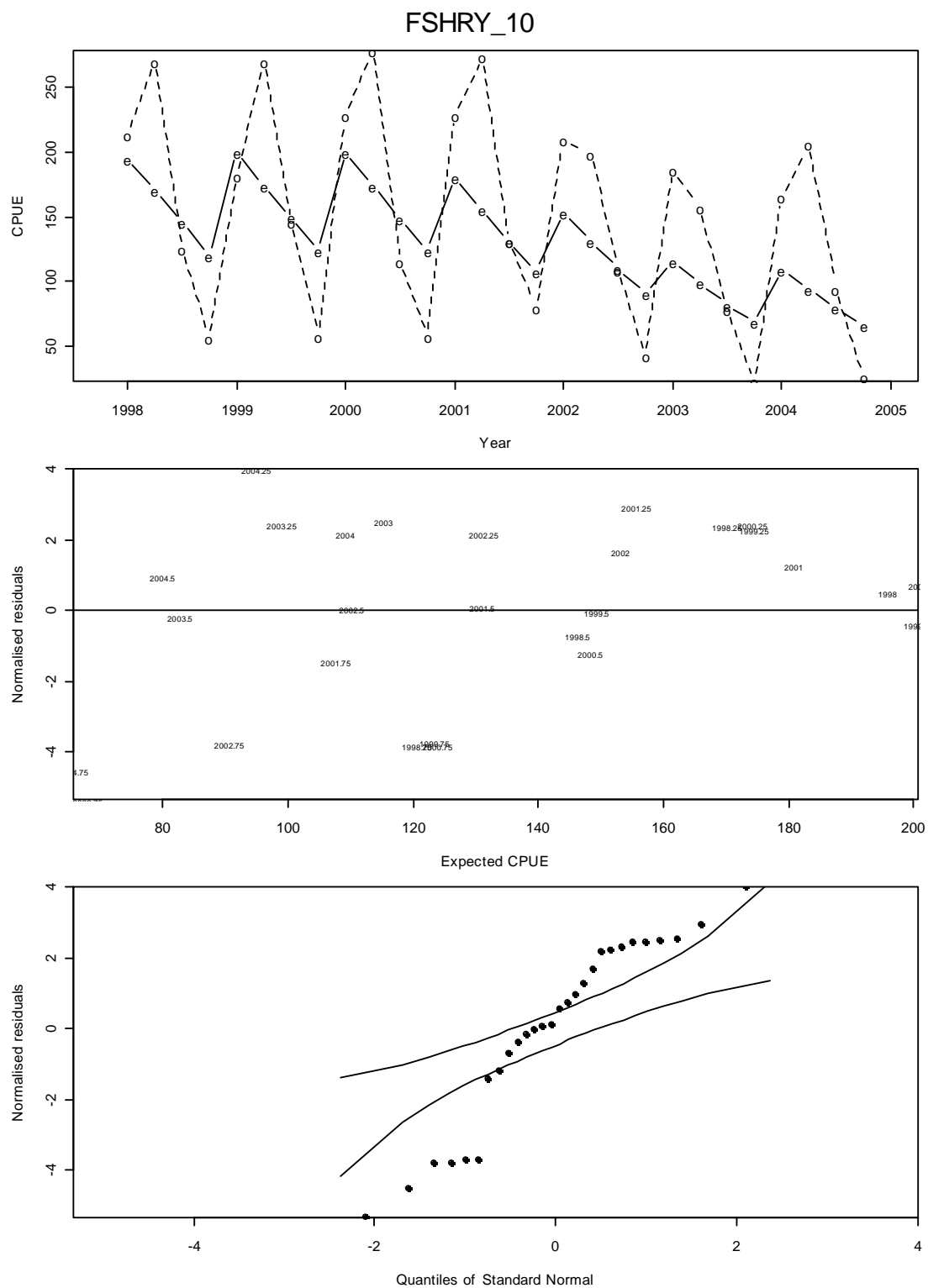
Figure 12: Swordfish CPUE for the NZ tuna longline fishery in Area 4 (top panel) showing observed (-o-) and fitted (-e-) values for the five-area model including foraging site fidelity (5AR_Fid), with diagnostic plots of the normalised residuals (bottom two panels).

Figure 13: Swordfish CPUE for the combined south-west Pacific longline fishery for the single-area models 1AR_1CP and 1AR_1CP50 (top and bottom panels, respectively) showing observed (-o-) and fitted (-e-) values.
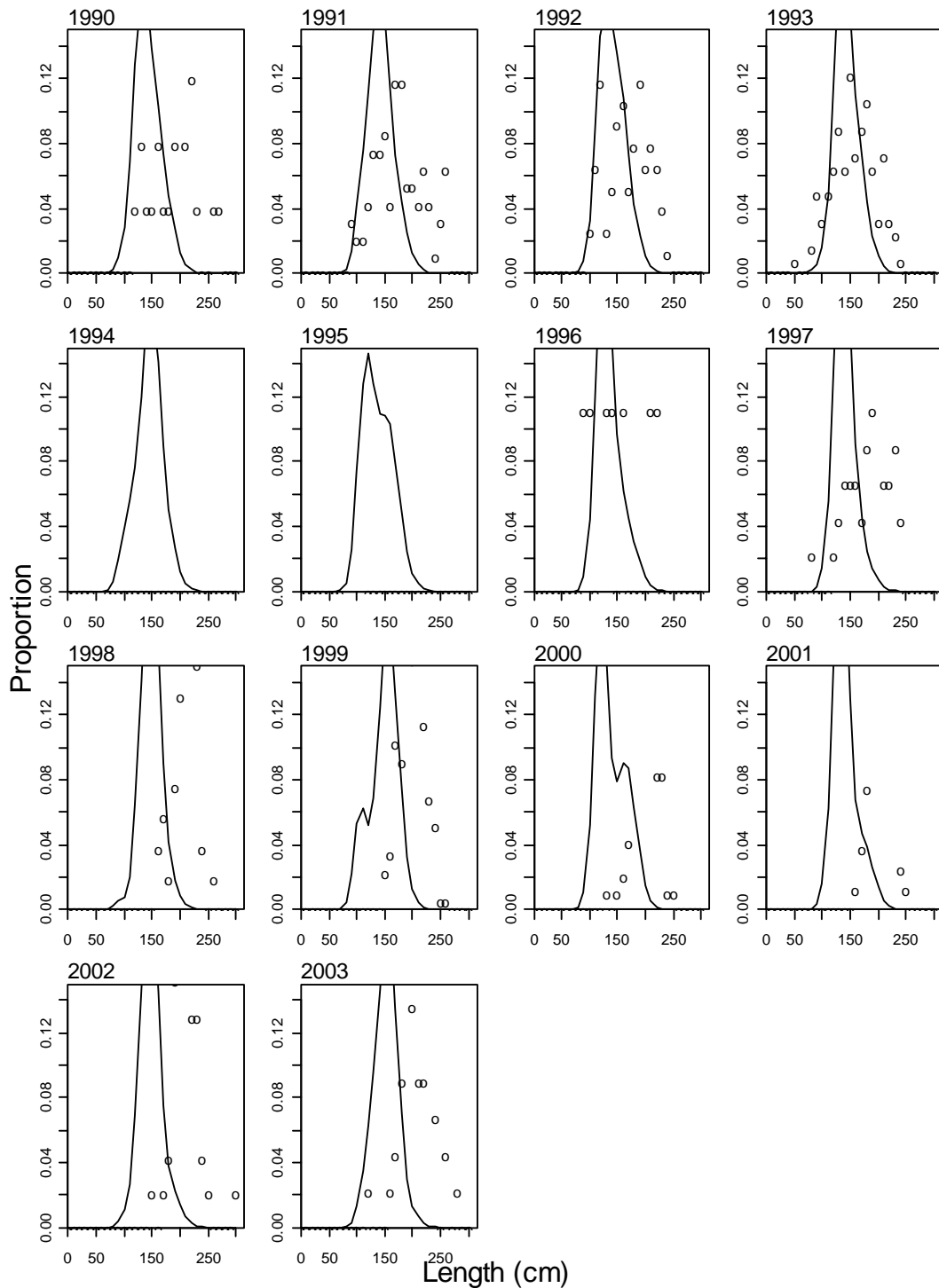
Figure 14: Swordfish catch-at-length time series for the AU tuna longline fishery in Area 2 in the second quarter showing observed (-o-) and fitted (-e-) values for the five-area model including foraging site fidelity (5AR_Fid).

Figure 15: Observed decline in mean length of swordfish caught in the AU fishery in Area 2 over quarters 1 to 4, with estimates for the five-area model including foraging site fidelity (5AR_Fid).

DP fleet-area 5-qtr 2 catch at length
FSHRY_5_2_length

Figure 16: Swordfish catch-at-length time series for the DP tuna longline fishery in Area 5 in the second quarter showing observed (-o-) and fitted (-e-) values for the five-area model including foraging site fidelity (5AR_Fid).
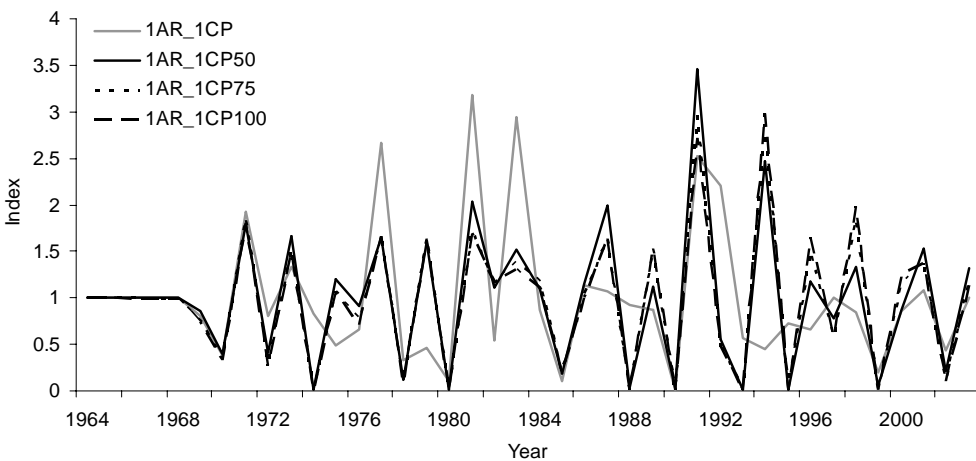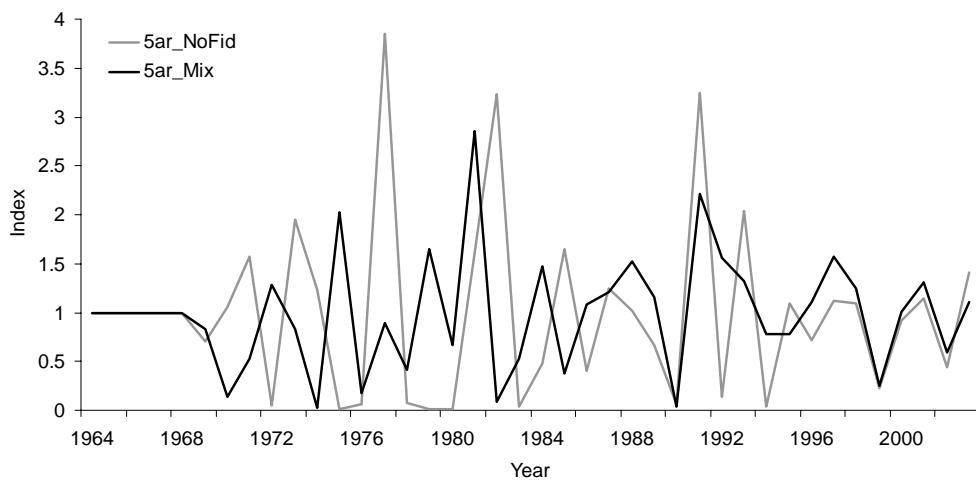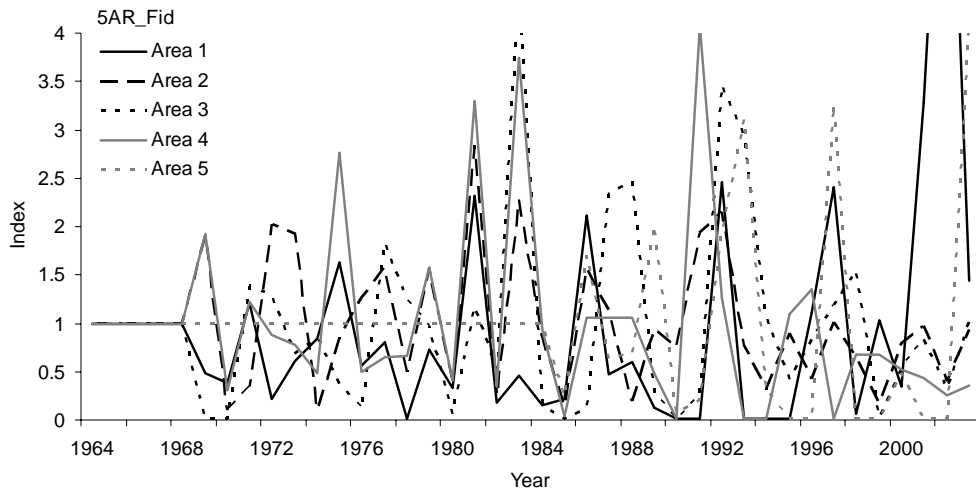
Figure 17: Year class strength (YCS) estimates in each area for the five-area model including foraging site fidelity (5AR_Fid, top panel), and for the five-area models excluding foraging site fidelity and allowing mixing (5AR_NoFid and 5AR_Mix, middle panel), and for the single-area models with alternative assumed relative weight on the catch-at-length likelihood term (bottom panel).
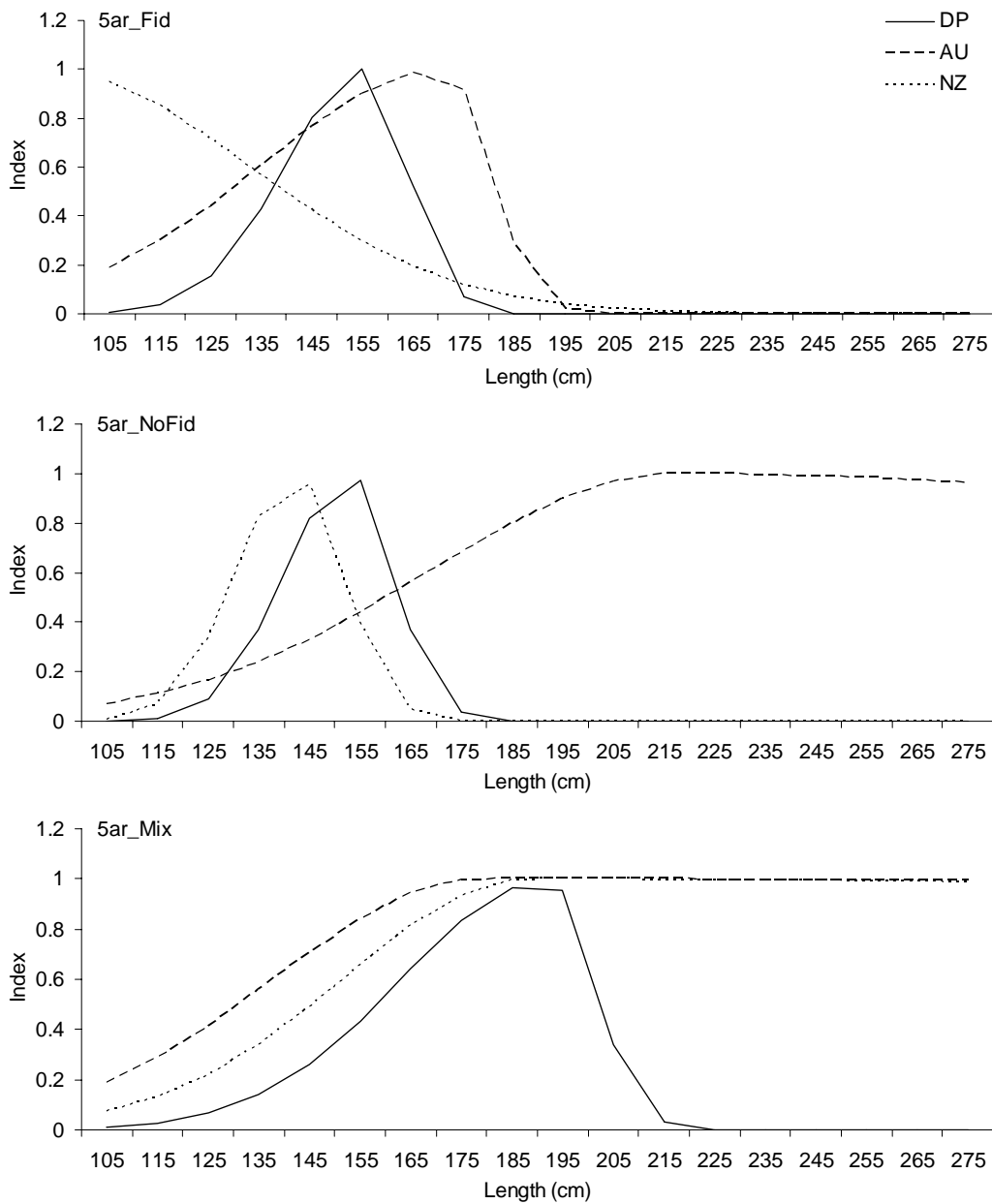
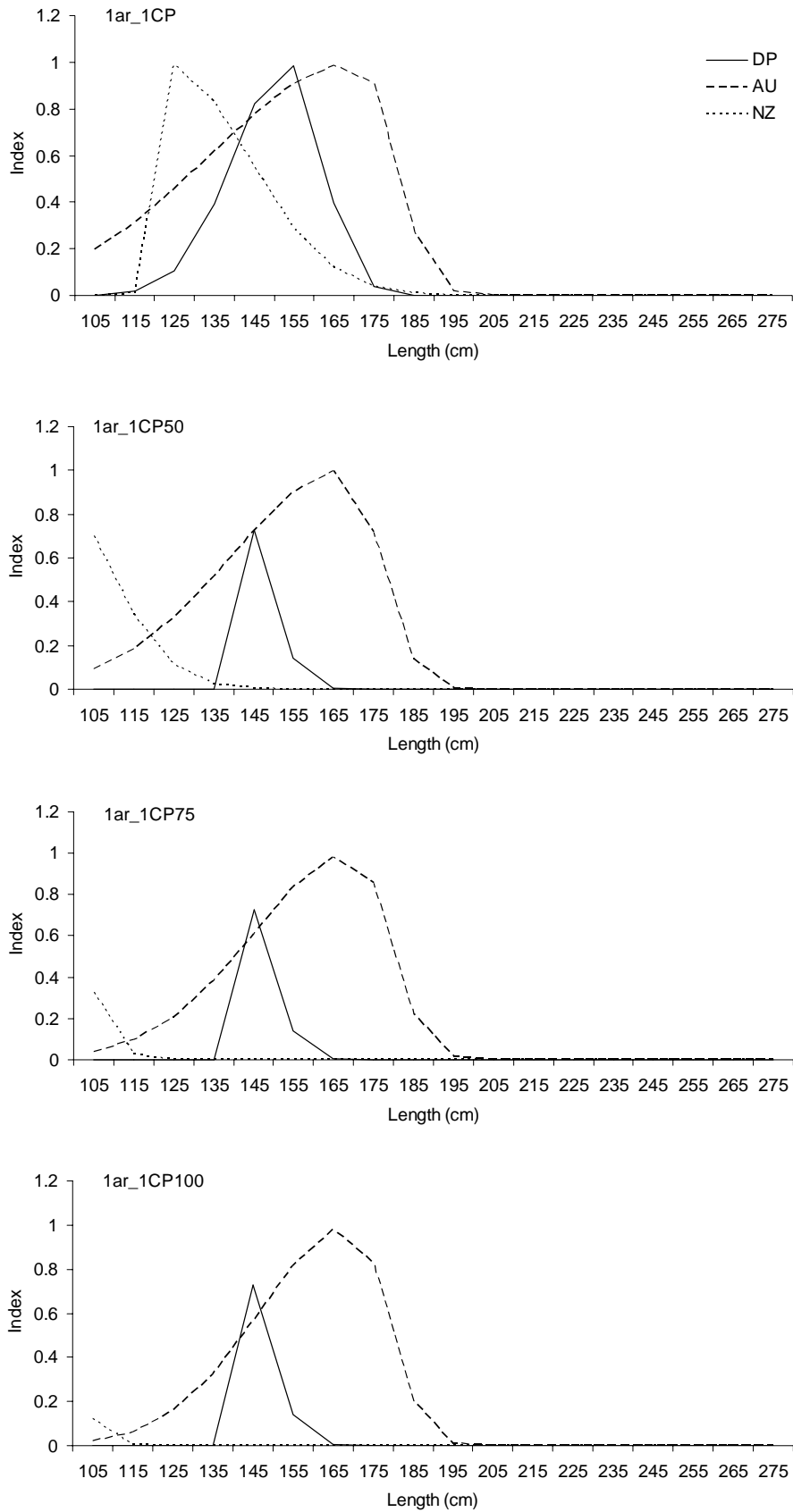Figure 18: Selectivity-at-length estimates for the five-area models.

Figure 19: Selectivity-at-length estimates for the single-area models
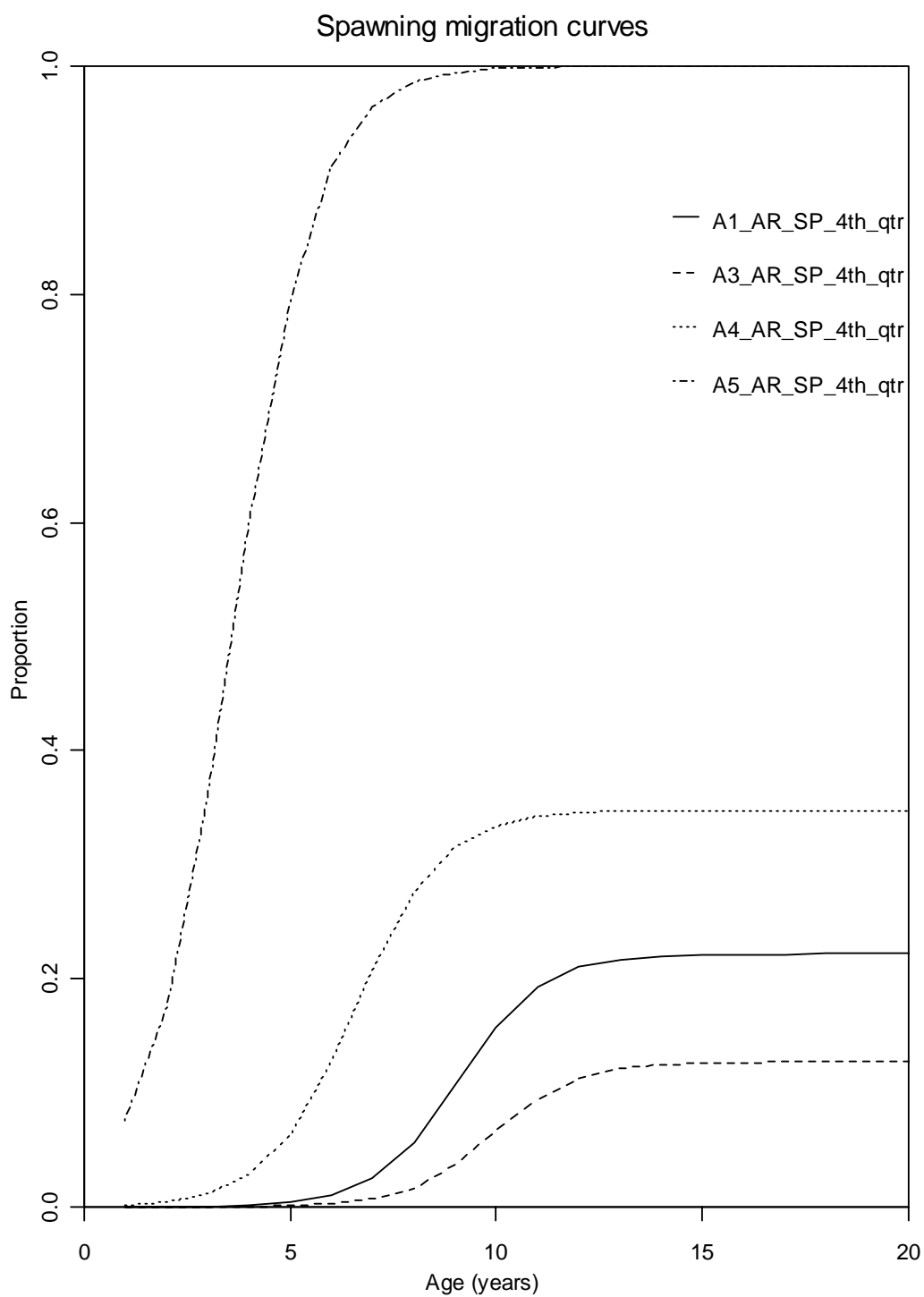
Figure 20: Estimated spawning migration ogives for the swordfish five-area model including foraging site fidelity (5AR_Fid), showing movement out of Areas 1 to 5 into the spawning area (AR_SP) at the beginning of the fourth quarter.
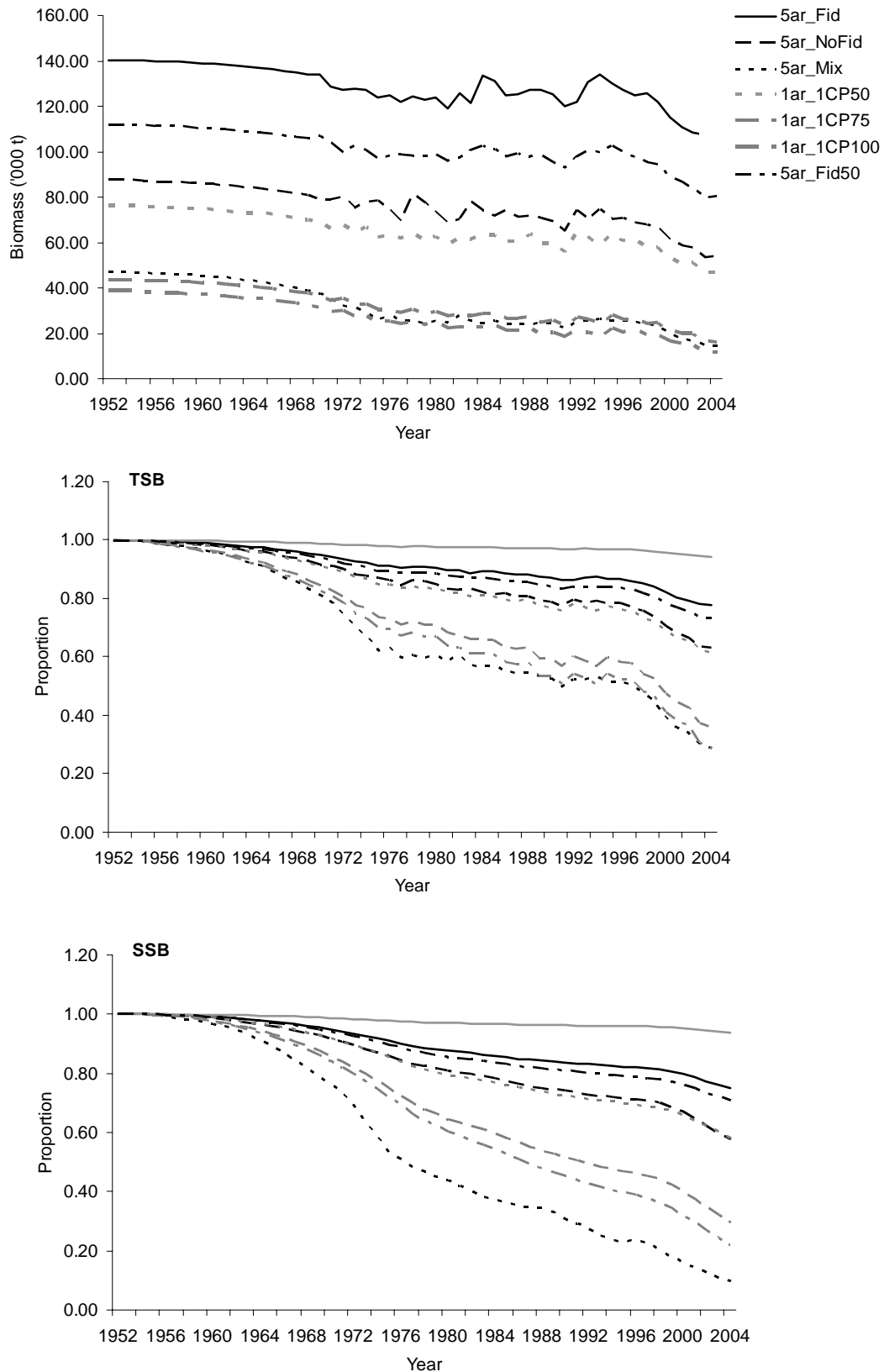
Figure 21: Model total stock biomass (TSB) estimates (top panel), and the relative
effects of fishing on total and spawning stock biomass (middle and bottom
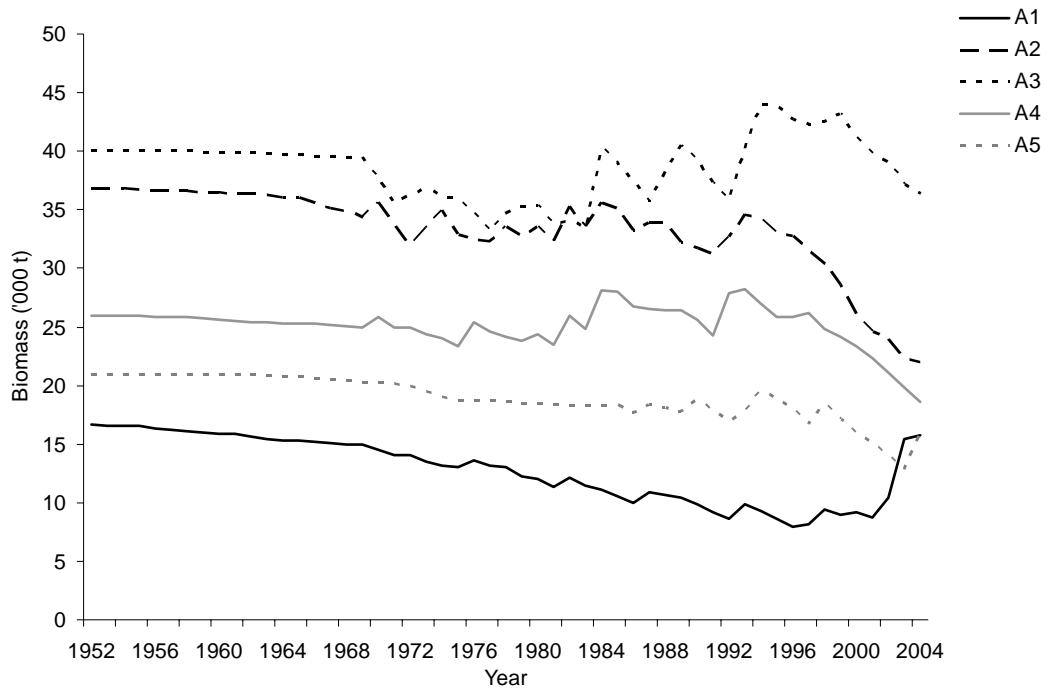panels, respectively). Note: model 1AR_1CP TSB is ~600 Kt and is not
shown.

Figure 22: Total stock biomass in each area of the five stock model including foraging site fidelity (5AR_Fid).

Appendix 1: CASAL modelling framework

CASAL (Bull et al. 2005) is similar to Multifan-CL being a complex, yet flexible, age-structured assessment modelling framework. A high level of population disaggregation may be implemented allowing the flexibility required in describing a sexually dimorphic species such as swordfish having apparently complex spatial dynamics, such as the foraging site fidelity and spawning migrations (Kolody et al. 2005).

The CASAL model may classed as an "integrative model" in that it describes fishing mortalities from multiple fleets, with disaggregation in respect of sex, age, area, stock, and maturity, with population transitions including age-, length-, and sex-specific migration ogives, and age-, length-, and sex-specific fishing and natural mortalities, and may be fit to a wide range of age-, length-, sex-, or area-specific observations. The population structure is defined in terms of:
- an annual cycle, being a sequence of annual processes acting on the population state;
- time steps, being annual divisions in which processes occur;
- states, i.e., the population state variable; and,
- transitions, being processes that change the population state variable.

The population state is defined in terms of partitions that stratify or disaggregate the population into units that include: age, length, sex, maturity, area, stock, tagged/untagged fish, and growth paths. Transition processes act on selected partitions in selected time steps with the following processes available: ageing, recruitment, maturation, migration, growth, mortality, disease mortality, tag release events, and tag shedding.

In any time step the annual age-structured population state vector may be projected to a length vector using either a mean or variable annual growth function. This allows the application of length-specific transition processes (mortality, migration) and to fit the model to length-frequency observations. Model fitting includes point estimation (maximum likelihood estimate, MLE, least squares, or the mode of the posterior distribution, MPD), and Bayesian parameter estimates can be calculated using the Monte Carlo Markhov Chain algorithm (MCMC). CASAL includes simulation capability and may readily be incorporated into a model evaluation framework.