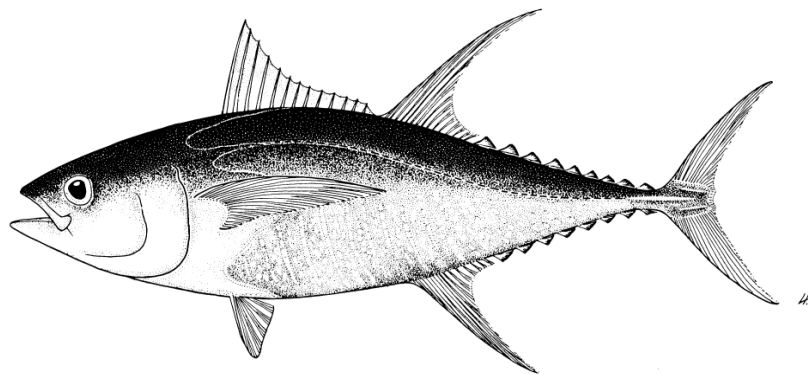


MWG-1



Testing the accuracy of MULTIFAN-CL assessments using an operational model of yellowfin tuna (*Thunnus albacares*) fisheries in the western and central Pacific Ocean



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Introduction

MULTIFAN-CL (MFCL) is a spatially disaggregated, length-based, age-structured model used for statistical catch-at-age analyses of fisheries data. The model uses information on total catch, fishing effort distribution, catch size frequencies, tag release-recapture, and prior knowledge on the fishery and fish biology to estimate length-at-age, mortality rates, fish movement, tag recovery and reporting patterns, biomass and recruitment trends, catchability coefficients, gear selectivities, spawner-recruit relation, and potential yields. The history and features of MFCL are well documented (Fournier *et al.* 1990; Fournier *et al.* 1998; Hampton and Fournier 2001, Kleiber *et al.* 2003), and scientists of the Oceanic Fisheries Programme (OFP) routinely use MFCL to assess tuna stock status in the western and central Pacific Ocean (WCPO).

Despite considerable testing during the model development stage, little is known on the accuracy of MFCL estimates based on actual fisheries data sets. Of particular concern is the potential bias of key estimates used to make management decisions. Since the application of the precautionary approach advocated by the United Nations Straddling Stock Agreement (U.N. 1995), fishing nations must use Precautionary Reference Points (PRPs) to manage fisheries. These include limit reference points used to constrain harvesting within safe biological limits, and target reference points used to meet the management objectives (ICES 1996).

Several PRPs were proposed over the past decade (FAO 1993). The merits of some points were investigated (Anon. 1993), and many agencies use them to formulate management plans (Restrepo *et al.* 1998; Boggs *et al.* 2000). Choosing the most suitable PRPs depends on data availability, fishery complexity, stock dynamics, management objectives, and the model's ability to estimate them accurately (Anon, 1993, Richards *et al.* 1998).

Three years ago, the OFP began investigating the accuracy of MFCL estimates obtained under certain conditions concerning fishery complexity, oceanic conditions, data availability, stock dynamics, and sampling methods. This was done with an operational model (Linhart and Zucchini 1986), that generates pseudo-observations using known parameter values, which are then compared to the estimates obtained by analysing the pseudo-observations. Hilborn and Walters (1992, p. 239) noted that using operational models should be an integral part of any stock-assessment. This approach is used by the National Marine Fisheries Service (NMFS) for swordfish assessments (Goodyear 1989; Labelle 2002), by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) to provide fishery management advice (Campbell *et al.* 1998), and by stock-assessment review committees in Europe and in North America (ICES 1993; NRC 1998).

The operational model (termed 'simulator') is designed to simulate key aspects of the dynamics of the WCPO yellowfin fishery, as described in Hampton and Fournier (2001). To a large extent, it has a structure and features common to individual-based models (Huge *et al.* 2002), and includes mechanistic sub-models for growth, natural mortality, spawning, recruitment, tag release and recapture, movement, and exploitation by multiple fisheries with different catchability and selectivity patterns. The simulator generates a variety of outputs on key components of the stocks and the fisheries, given sampling regimes, and user-specified levels of process and observation errors. The simulator operates on a spatial and temporal resolution of $5^{\circ} \times 5^{\circ}$ by month, with outputs aggregated into a coarser stratification for analysis by MFCL.

During 2002, the Method Work Group (MWG) of the Standing Committee on Tuna and Billfish (SCTB) relied on the simulator to provide insight into the accuracy of biomass ratio estimates obtained with MFCL, the Fox production model (Fox 1975), SCALIA (Kolody 2002), A-SCALA (Maunder 2002), and ADAPT (Gavaris 1988, Conser 1993). The MWG noted that MFCL and other complex models estimated the ratios of certain population parameters with acceptable accuracy (Anon. 2002). The MWG requested that multi-model testing be continued to investigate the effects of spatial stratification, tagging information, exploitation levels and data variability on the accuracy of the PRP estimates.

This paper summarizes the developments related to the latest tests requested by the MWG. It describes the features of the simulator, the fishing scenarios used, the testing procedure and the results obtained. It is beyond the scope of this paper to discuss the large spectrum of conditions faced by scientists when analysing fishery data, or to comment on the relative performance of various models in unique contexts. This paper focuses only on the performance of MFCL when analysing simulated data considered as plausible sets of observations stemming from the WCPO tuna fisheries. To minimize redundancies and duplications, the reader is encouraged to consult Hampton and Fournier (2001) for background information before reading what follows.

Materials and Methods

Simulator structure and exploratory testing

The simulator initially builds up the population deterministically in the absence of exploitation. Fish recruit to some regions, then grow, move about, reproduce and die from natural mortality. Once the abundance by region stabilizes, stochastic processes are enabled, and the population is subject to exploitation during the following years. All fishing effort series available to the OFP are used to specify the spatial and temporal trends in exploitation, and actual tag release patterns are used to simulate tagging experiments (Table 1). Given fishing effort, catch sampling and tag reporting rates, the simulator generates catch trends, size frequencies from catch samples, and tag returns by time/area/fishery stratum. The data generated can be contaminated with user-specified errors of various types (Fig. 1). The information sources and mathematical specifications of the simulator are given in appendices A and B, respectively.

The model is designed to ensure that the data produced meets some of the key underlying assumptions of MFCL, with regards to allowable error ranges and parameter variability. However the simulator functions differ from those of MFCL, and both models operate on different spatial and temporal scales. Consequently, the simulator cannot generate data that meets all MFCL assumptions, and the users can generate data that do not meet even the key assumptions (more later on this).

Once the simulator became operational, several tests were done to minimize the possibility that the code contains logic or programming errors. This involved comparing the outputs of various functions to those of numerical libraries, statistical applications, and other assessment models. The functions were also supplied with erroneous or unrealistic input values to ensure they could be detected. To determine if the simulated trends are realistic and reliable, over 100 simulations were made. With minimal scaling and function calibration (e.g. set baseline catchability rates, etc.), the catch trends, sex-ratios in catch samples, tag recovery patterns, and catch length frequency distributions conformed well with expected patterns. Data were then generated under overly simplistic conditions (no errors, many parameter values fixed, etc.) and submitted to preliminary MFCL analyses. Estimates of biomass, M-at-age, length-at-age, gear selectivity, recruitment, and catches were close to or equal to the simulated values. The exploratory testing phase ended when no coding or logic errors were detected, and no further adjustments could be justified.

MFCL evaluation procedure

Testing was conducted by means of Monte Carlo simulation procedures. For each fishery scenario investigated, multiple data sets are generated and then analysed using a single MFCL set-up configuration (see Kleiber *et al.* 2003). Each data set is obtained with a unique combination of random numbers, and is considered to represent one possible set of observations from a fishery realisation. For each scenario, 40 realisations were made. For moderately complex scenarios, generating and analysing 40 data sets takes 10-20 d of computing time on PC with a 1.6 GHz Pentium4 processor

and 1 GB of RAM, so the number of realizations tested was largely dictated by time restrictions and the availability of computing resources.

The tests were conducted with MFCL version 3, which produces a large number of statistics used for diagnostics, and up to 5000 parameter estimates. The tests focus primarily on well known PRPs and other parameters of biological interest, including length-at-age, M-at-age, MSY, B_{msy} , F_{msy} , B_{msy}^s , B_t/B_{msy} , F_t/F_{msy} , B_t^s/B_{msy}^s , recruitment time series, and overall harvest rates (catch/abundance, in numbers). Two additional indicators are computed given that both MFCL and the simulator also predict time series of abundance that would have occurred in the absence of exploitation (Fig. 2). For exploited trends, the final to initial biomass ratio ($Q_1=B_{end}/B_{start}$) has traditionally been considered as an indicator of current stock condition relative its initial state (i.e virgin biomass). However, from a theoretical point of view, B_{start} may not represent virgin biomass, Q_1 may not account for changes in ocean conditions that affect productive capacities. So an alternative indicator of stock condition is computed ($Q_2=B_{end}/B_{end}^*$) from the final biomass levels of the exploited and unexploited trends.

For all PRPs, parameters and indicators generated, the ratio of the estimated to simulated values is computed for each realisation. The inter-quartile range (Chamber *et al.* 1983) of the ratios is computed over all realisations to show trends in central tendency (median) and variability (25%-75% quantiles). When the median is >1.0 , the estimates tend to exceed the actual values, and are qualified as being positively biased. No overall measure of accuracy and precision is computed, as this involves subjectively weighting each trend to compute an overall goodness of fit. Instead, attention is drawn to each trend to identify the most reliable PRPs and indicators under specific scenarios.

Description of MFCL test scenarios

The fishery scenarios were formulated so as to be increasingly complex and informative. The last scenario is the best representation of the WCPO fishery, with 16 fisheries operating in seven zones (see Hampton and Fournier 2001). These include three fisheries with small-scale gears (handlines, gillnets, etc.) in the Philippines and Indonesia, and 13 large commercial fisheries comprised of six purse-seine (PS) and seven longline (LL) fleets. For other scenarios, many simplifications were made. The same fishing period applies, but some of the 16 fishing effort series are omitted. The number of fishing zones is reduced, but the sum of all zones used always cover the entire WCPO, and the data are aggregated accordingly.

Unless specified otherwise, the basic scenario upon which others are built involves von Bertalanffy growth with a linear relation between the standard deviation and the mean length-at-age, M-at-age trends in the range of 0.2-0.4 per quarter (Type_2, Fig. 3), with no sexual differences in growth and natural mortality. Time-invariant and fishery-specific catchability and selectivities. Overall harvest rates were adjusted to be $\approx 20\text{-}30\%$ of average natural mortality rates, which was sufficient to reduce the total biomass to levels close to MSY (Fig. 4). Fixed proportions at maturity that match those hypothesized in MFCL. Proportional size sampling (2%) of catches across all strata, 100% tag

reporting rate, no SOI effects on movement, and identical stochastic variation levels in recruitment for all scenarios.

Scenario 1: Single longline fishery, single zone. Recruitment range ≈ 70 -220 million fish per quarter. Sigmoid selectivity curve allowing the youngest age groups (recruits) to contribute to catches.

Scenario 2: Two fisheries (LL, PS) operating in a single zone. Purse seine effort deployed mainly over the equatorial band. Each fishery with unique selectivity pattern, but the youngest age groups only contribute to longline catches.

Scenario 3. WCPO split in two zones, east and west of 180° . Two fisheries (LL, PS) in each zone. Each fishery with a distinct selectivity and catchability pattern. Selectivity patterns are such that the youngest age groups contribute to catches of one longline fishery only.

Scenario 4. Seven longline fisheries, each operating in one of seven zones. Selectivities conform to one of two patterns, one of which allows catches of youngest age groups. Seasonal variation in catchability of fisheries in northern and southern zones. Fishery-specific catchability rates that increase $1\% \cdot \text{yr}^{-1}$, and are subject to stochastic variation. Fixed fishery-specific tag reporting rates in the 17-56% range.

Scenario 5. Sixteen fisheries operating in seven zones. Yellowfin growth pattern, with sex-specific growth rates. Type_1 natural mortality pattern, with sex-specific mortality rates. Seasonal variation in catchability for longline fisheries in northern and southern zones. Catchability rates of all longline fisheries increase $0.5\% \cdot \text{yr}^{-1}$. Stochastic variation in catchability for all fisheries. Time-invariant fishery-specific selectivities and tag reporting rates. SOI effect on movement is enabled.

Results

Scenario 1: Length-at-age estimates conform well with simulated values (Fig. 5). The bias in M-at-age is not consistently positive or negative across all ages. Biomass time series show varying levels of bias, with spawning biomass series showing more bias. Time series of exploitation rates tended to be positively biased. Recruitment series were negatively biased, possibly due to the negative bias of M-at-age for the youngest age groups. Bias levels in time series of B-ratios (B/B_{msy} , B^S/B_{msy}^S), and F-ratios (F/F_{msy}) mirror the corresponding biomass and exploitation rate series. PRPs and indicators are within $\pm 25\%$ of actual values.

Scenario 2: Length-at-age estimates conform well with simulated values (Fig. 6) M-at-age estimates show substantial bias, as are the time series of biomass, spawning biomass, and recruitment. As in scenario 1, biomass time series are less biased than the spawning biomass series. Biomass ratios and F-ratio time series are most biased in the final years. PRPs and indicators are

within $\pm 40\%$ of actual values. In general, the bias levels appear greater than in scenario 1, despite the fact that the data sets in this scenario uses information from an extra fishery.

Scenario 3: Length-at-age estimates conform well with simulated values (Fig. 7). M-at-age estimates are as biased as in scenario 2, but time series of biomass and spawning biomass show less bias. In general, the bias levels of various time series tend to be equal to or less than that seen in Scenario 2, which may reflect the small positive influence of additional spatial stratification and information from two additional fisheries. Most PRPs and indicators are within $\pm 30\%$ of actual values.

Scenario 4. Length-at-age estimates conform well with simulated values (Fig. 8). M-at-age estimates are substantially biased over ages 7-11. Recruitment series conforms well with the actual series, partly because M-at-age for the youngest age group is less biased. Biomass and spawning biomass series are now positively biased. Biomass ratios and F-ratio trends show little or no bias, partly because of the positive bias in B_{msy} and B_{msy}^s . Exploitation rates show little bias. In general, there appears to be a slight increase in the variability of biomass, recruitment and exploitation rate estimates. Most PRPs and indicators are within $\pm 40\%$ of actual values.

Scenario 5. Length-at-age estimates conform well with simulated values (Fig. 9). M-at-age estimates obtained showed trends that appeared unrealistic for the middle age groups (five times the average rate). The MFCL analysis was redone after specifying that only an average M be estimated and applied to all age groups. Consequently the trends still indicate some bias in M-at-age. Recruitment series is negatively biased due to bias in M-at-age for the youngest age. Biomass and spawning biomass series are slightly biased. Biomass ratios and F-ratio trends show little or no bias, partly because of the bias in B_{msy} and B_{msy}^s . Estimated exploitation rates are nearly double the actual rates. PRPs and indicators are within $\pm 50\%$ of actual values.

Discussion

The results provide only insight into the relative accuracy of some MFCL estimates. Despite the precautions taken to ensure that tests were done correctly, the possibility remains that external factors caused MFCL to provide estimates that are biased or appear biased. These include logic or programming errors in the simulator code, using data sets with insufficient detail or contrast, or misconfiguring MFCL before doing an analysis (wrong flags, priors, penalties, etc.). Also, the Monte Carlo procedure used dictates that all analyses were done in a 'generic' fashion, so analyses cannot be modified while underway to improve convergence or deal with any anomaly detected. In view of such facts, the results presented can be viewed as being worst than could be obtained by a skilled analyst with considerable background knowledge of the fishery and the stocks exploited.

The fact remains that some of the MFCL estimates shown were substantially biased. M-at-age estimates were the most inaccurate of all. Exploratory testing conducted so far did not show that this was due to some simple parameter confounding, such as say between selectivity and natural mortality. Further testing is required to determine the nature of the factor responsible for various biases. Still, until further tests can demonstrate that the M-at-age estimates are accurate, estimates of average M may be biased as well, and the reliability of some proxy-based reference points may be problematic (e.g $F_{msy} = 0.8 M_{average}$, as in Restrepo *et al.* 1988).

Biases in M-at-age cause other estimates to be biased, recruitment trends for one, and other absolute values that are a function of natural mortality. However, it is a well known fact that some stock-assessment models provide estimates of relative values (i.e ratios) that are more accurate than those of absolute values, often because of positive correlations between the numerator and the denominator. This appears to be the case for MFCL as well. For the most complex fishery scenarios, time series of F-ratios and B-ratios were very accurate despite biases in the estimated biomass time series and the PRPs. The lack of substantial bias in the F-ratio and B-ratios during the final periods is a particularly important finding, since the ratios are an accurate reflection the most recent condition of the population relative to MSY levels, and provide fishery managers the information they need to determine if the population is overfished, and if there is justification for imposing 'control rules' (Restrepo *et al.* 1998, Boggs *et al.* 2000).

The results suggest that greater spatial stratification and more informative data sets lead to improvements in the accuracy of the remaining indicators as well, namely Q_1 , Q_2 , which are also relative values. Only for the most complex scenario were both figures within $\pm 12\%$ of the actual ones. The difference in accuracy between indicator Q_1 and Q_2 is negligible, so managers have the choice of using the conventional measure of fishing impact (Q_1), or opting for the alternative indicator (Q_2) based on theoretical merits.

The tests conducted so far suggest that with the information available at SPC, the OFP can use MFCL to obtain an accurate picture of the current condition of the yellowfin population in the WCPO, and provide estimates of PRPs that may be sufficiently reliable for management purposes, at least under certain catch sampling regimes. While these preliminary results seem encouraging, additional investigations are underway to assess the benefits of using new or additional sources of information (tuna weight data, additional tagging information, modified catch sampling operations, etc.), as well as the effects of different types of observation errors. Hopefully, this will reveal the nature of the factors responsible for biases in certain parameter estimates, and help determine how to best allocate the limited financial and human resources available to increase the cost-benefit ratio of stock and fishery monitoring operations.

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Appendix A. Symbols and Notation

i	= index denoting a 2cm length category (range: 1-100)
a	= index denoting an age group in months (range: 1-84)
w	= index denoting a 1 kg weight category (range: 0-200)
s	= index denoting the sex category (male = 0, female = 1)
y	= index denoting a calendar year (range: 1-37)
t	= index denoting the month of the year (range: 0-12)
v	= index denoting a fishery with a specific vessel type (range: 1-16)
x_i	= mid-point on the 2 cm length interval of category i
P_{ia}	= probability of age a fish being in length interval i
P_{iw}	= probability of weight w fish being in length interval i
P_{wi}	= probability of length i fish being of weight interval w
K	= von Bertalanffy (VB) annual growth rate coefficient
G_a	= growth rate reduction coefficient, age a
ρ	= Brody growth coefficient
a^*	= age of maximum growth rate reduction
b	= coefficient proportional to maximum decrease in K at $a=a^*$
L_1, L_A	= mean fork length of first and last age groups on the VB curve, month 1
$\mu_{L,a}$	= mean of length distribution of age a fish
$\sigma_{W,i}$	= standard deviation of the weight distribution of length i fish
N	= number of fish
M	= natural mortality rate
f	= standardised fishing effort
F_i	= fishing mortality rate on fish in length interval i
F'_a	= effective fishing mortality rate on age a fish
Z	= total mortality rate
C	= catch
q_v	= baseline catchability coefficient, fishery v
S_{vi}	= selectivity of gear v , on fish in length interval i
R	= number of recruits
D_i	= daily travel distance ($\text{km} \cdot \text{d}^{-1}$) for fish in length interval i
\vec{D}_{N-S}	= school displacement vector ($\text{km} \cdot \text{mo}^{-1}$), north-south plane
T	= time interval (d)
B, B^S	= exploited biomass and spawning biomass (mt)
B^*	= unexploited biomass (mt) expected under $F=0$ for all quarters
Q_1	= ratio of biomass ($B_{\text{end}}/B_{\text{start}}$)
Q_2	= ratio of exploited to unexploited biomass in the last three quarters
Y	= yield (mt)
h_n, c_n	= generic model coefficients
SST	= sea surface temperature
SOI	= southern oscillation index
Γ_i, Γ_a	= proportion of fish in a length or age category that are mature
∇	= SST gradient index
ε	= random error term
ω	= residual deviation
α	= maximum number of recruits per spawning biomass unit
β	= spawning biomass (mt) required to produce $\alpha/2$
$\phi_a(x)$	= index of abundance-per-recruit for age a , F-multiplier x
$\Phi(x)$	= index of biomass-per-recruit, for F multiplier x

Appendix B. Simulator components

Environmental structure

The area covered is 40°S - 40°N, and 110°E - 150°W, split into a grid of 320 regions of 5°X5° in longitude and latitude. Marginal regions and those over land masses are omitted, so 247 regions are used to distribute fish and fishing effort. Computations are done in monthly time steps over 1962-98, yielding 444 periods, or 109,668 time/area strata. Each stratum is assigned a sea surface temperature (SST) obtained from an ocean circulation model (Chai *et al.* 2001; Dugdale *et al.* 2001).

Population structure

All fish recruiting to a region/month stratum form a school, whose members grow and move together until the last one dies. A maximum of 247 new schools can be created each month. Recruitment occurs after 60 d of growth, and maximum longevity is 84 months, so the model can track 20,254 schools each month during a simulation. Several schools can occupy the same stratum. There is no exchange of fish between schools, but all mature fish in a stratum can spawn together.

Growth

Length-at-age is computed with the von Bertalanffy model formulation of Schnute and Fournier (1980), re-parameterised to account for a growth reduction in early life (Lehodey and Leroy 1999). The standard deviation to mean length-at-age relation is modelled as a linear function to comply with MFCL assumptions, or as a quadratic function that provides a better fit the observations of Lehodey and Leroy (1999). These show increasing spread in length-at-age up to about 0.6 L_A , followed by a gradual reduction, perhaps due to variation in K within the population (Rosenberg and Beddington 1998). The probability that a fish is in a 2 cm length interval is computed from

$$(1) \quad G_a = \frac{b}{\sigma\sqrt{2\pi}} \exp\left\{\frac{-(a-a^*)^2}{2\sigma^2}\right\}$$

$$(2) \quad \rho_a = \exp(-K + G_a)$$

$$(3) \quad \mu_{L,a} = L_1 + (L_A - L_1) \left\{ \frac{1 - \rho_a^{a-1}}{1 - \rho_a^{A-1}} \right\}$$

$$(4) \quad \sigma_{L,a} = c_1 + c_2 u_{L,a} + c_3 u_{L,a}^2$$

$$(5) \quad P_{ia} = \frac{1}{\sigma_{L,a}\sqrt{2\pi}} \exp\left\{\frac{-(x_i - u_{L,a})^2}{2\sigma_{L,a}^2}\right\}$$

With age expressed in months since birth, the parameter values used for males are $A=84$, $L_1=15.445$, $L_A=140.896$, $K=0.073$, $a^*=10.721$, $\sigma=4.575$, and $b=0.288$. For females, $A=84$, $L_1=19.573$, $L_A=153.032$, $K=0.056$, $a^*=10.362$, $\sigma=3.639$ and $b=0.152$. Using SPC length-at-age records for both

sexes combined, the best fitting estimates for c_1 , c_2 and c_3 were -6.121, 0.325 and -0.002. When a linear function is implied, these parameters are arbitrarily set to 0.00, 0.10 and 0.00. The simulator allows users to specify $G_s=0$, and identical length-at-age for both sexes, in which case growth conforms strictly to the von Bertalanffy model, with no sex-specific differences.

Weight-length relation

Examination of 16,000 length-weight measurements from OFP records suggests that the relation between total weight (in kg) and fork length (in cm) conforms to a power function, and the standard deviation to mean relation in weight-at-length is linear over the range of observations. The probability that a fish in a 2 cm length interval is in a 1 kg weight interval is computed under the assumption that the weight-at-length distribution is normal.

$$(6) \quad \mu_{w,i} = 0.000017593i^{3.0}$$

$$(7) \quad \sigma_{w,i} = 0.1485 + 0.0972 \mu_{w,i}$$

$$(8) \quad P_{wi} = \frac{1}{\sigma_{w,i} \sqrt{2\pi}} \exp \left\{ \frac{-(x_w - \mu_{w,i})^2}{2\sigma_{w,i}^2} \right\}$$

Length-weight relation

OFP records indicate that the relation between fork length and total weight conforms to a power function, and the standard deviation to mean relation in length-at-weight is linear over the range of observations. The probability of fish in a weight category being in a length category is computed under the assumption that the length-at-weight distribution is normal.

$$(9) \quad \mu_{L,w} = 38.552 w^{0.334}$$

$$(10) \quad \sigma_{L,w} = 4.0930 - 0.0009 \mu_{L,w}$$

$$(11) \quad P_{iw} = \frac{1}{\sigma_{L,w} \sqrt{2\pi}} \exp \left\{ \frac{-(x_i - \mu_{L,w})^2}{2\sigma_{L,w}^2} \right\}$$

Natural mortality

Yellowfin are thought to be subject to high natural mortality in early life, which decreases until maturation, then increases up to 135 cm, and finally decreases again due to the attrition of females subject to higher mortality rates (Anon 2000; Hampton and Fournier 2001). A cubic function relates natural mortality and fork length for males and females separately.

$$(12) \quad M_i = c_0 + c_1 i + c_2 i^2 + c_3 i^3$$

For the M-at-age trends reported by Hampton and Fournier (2001), the best fitting values obtained for parameters c_0 - c_3 were 9.548422, -0.334335, 0.003979 and -0.000014 for males, and 14.94001, -0.50767, 0.005696, and -0.0000195 for females. The resulting trend (Fig. 3, Type_1) is similar to that of Hampton and Fournier (2001), and translate into slightly higher male:female ratios in the 50-100 cm size range, as observed in SPC longline catch samples. A second mortality curve can be used as an alternative trend for testing purposes (Fig. 3, Type_2).

Spawning activity

To simplify the patterns described by Suzuki (1994) and Itano (2001), the model allows spawning to occur once a month, in all regions within 10°S-10°N, or in strata with increasing SSTs that are >24.5°C. It is implicitly assumed that all mature fish spawn, fecundity is size-independent, there are no competition for mates, no Allee effects at low densities (Allee *et al.* 1949), and no island-mass effects on spawning behaviour or larvae survival (Moore and Sander 1977). The proportions-at-maturity can be arbitrarily fixed based on ages (e.g. 0.0 for 2-21, 0.5 for 21-24, 1.0 for 25-84) to meet the MFCL assumptions, or computed from lengths using a logistic equation parameterised based on SPC bio-sampling records. For length-based calculations, spawning biomass is obtained from

$$(13) \quad \Gamma_i = \frac{1}{1 + e^{18.03 - 0.167i}}$$

$$(14) \quad B^S = 0.001 \sum_{i=1}^I \sum_{w=1}^W w N_i P_{wi} \Gamma_i$$

Recruitment patterns

The numbers of recruits in a time/area stratum is computed with the Beverton-Holt (1957) function, from the spawning biomass in the stratum, with no time lag between spawning and recruitment, and no pre-juvenile movement prior to recruitment.

$$(22) \quad \varepsilon_t \sim N(0, \sigma_R^2)$$

$$(15) \quad R_t = \frac{\alpha B^S e^{\varepsilon_t - 0.5\sigma_R^2}}{\beta + B^S}$$

Parameters α , β and σ_q were fixed at 550,000, 2300, and 1.8, to produce recruitments within the same order of magnitude as those reported by Hampton and Fournier (2001). Since many regions have spawning biomass but no suitable spawning conditions, these parameter values do not apply to the entire population. At the end of each simulation, these 'global' parameter values are estimated with the simplex algorithm (Press *et al.* 1992) using the 444 month time series of total spawning biomass and total number of recruits. Estimates are obtained by minimizing the sum of squared deviations between the natural logarithms of the predicted and observed recruitments. Sixty re-starts

with random parameter values were conducted during each search, which was found sufficient to reduce the chances of converging towards a false minima.

Fish movement

Daily displacements are computed using an exponential function fitted to the data reported by Brill *et al.* (1999) on lengths versus swimming speeds. From this, monthly school displacements are modelled as a two-dimensional random walk. The probability of moving in one of two directions is assumed to be a binomial process, so when $p=0.5$, a school is thought to travel travel back and forth to end in its initial position. The probability of ending at a certain distance from a starting position after a month ($T=30$) is computed using the normal approximation to the binomial

$$(17) \quad D_i = 131.51114 (1 - \exp(-0.0141741i))$$

$$(18) \quad P_i(x, x + \delta x) = \frac{1}{2D_i \sqrt{2\pi p(1-p)T}} \exp\left[\frac{-(x - TD_i(2p-1))^2}{8TD_i^2 p(1-p)}\right] \delta x$$

School displacements are predicted over a range of probabilities, using the transformation method described by Press *et al.* (1992). The cumulative probability distribution forms a definite-integral curve over probabilities 0-1 with maximum displacements of ± 3000 km. Two uniform random deviates are generated, representing positive or negative displacements, with the later indicating southward or eastward displacements. Since D_i represents a total displacement, half of it is taken as the displacement vector in each plane ($\vec{D}_{N-S}, \vec{D}_{E-W}$).

Factors like SSTs and ENSO events affect tuna distribution (Lehodey *et al.* 1997), with longitudinal displacements increased during La Nina and El Niño episodes. The southern oscillation index (SOI, Chen 1982) is used to condition movement. The 1962-98 indices range from -4.7 to 7.5, with negative values corresponding to eastward displacements of the warm pool and the tuna biomass (Lehodey *et al.* 1997). The indices are re-scaled to a range of ± 4.7 , and used to adjust the E-W displacement probabilities of schools within the equatorial band, west of 155°E for negative SOI values, and east of 155°E for positive SOI values.

$$(19) \quad p = 0.5 + 0.25 \left(\frac{SOI}{4.7} \right)$$

SSTs are used to condition latitudinal displacements. Movement is unconstrained between regions with SSTs $> 26^\circ\text{C}$, or when going to a warmer region ($SST_{\text{origin}} < SST_{\text{destination}}$). In other cases, a gradient index (0.0-1.0) is used to reduce movement to colder regions. Any reduction in N-S displacement is added to the E-W displacement, such that the total distance travelled is the same

$$(20) \quad \nabla = \begin{cases} 0.0 & SST_1 - SST_2 > 5^\circ \\ 1 - ((SST_1 - SST_2)/5) & SST_1 - SST_2 \leq 5^\circ \\ 1.0 & SST_1 < SST_2 \\ 1.0 & SST_1 \& SST_2 > 26^\circ \end{cases}$$

$$(xx) \quad \vec{D}_{N-S}^* = \nabla \vec{D}_{N-S}$$

$$(xx) \quad \vec{D}_{E-W}^* = (\vec{D}_{N-S}^* - \nabla \vec{D}_{N-S}) + \vec{D}_{E-W}$$

School movement is thus a mixture of biased and unbiased random walks, and is assumed to occur instantaneously at the beginning of each month. The resulting patterns agree with the figures reported by Suzuki (1994) and Sibert and Hampton (2003), with few schools migrating >1000 km during their lifetime, many more staying within 300 km of their recruitment area, and with E-W displacements usually exceeding N-S displacements.

Fishing effort distribution

For yellowfin assessments, Hampton and Fournier (2001) distributed fishing effort into 16 fisheries, and 7 fishing zones. These 16 effort series, or any combination of these can be used for computing catches. For Indonesian and Philippe fisheries (1-3), nominal effort values are unavailable to SPC so catches are used as proxies. For longline fisheries, effort consists of numbers of hooks deployed per strata, standardised to account for yellowfin habitat preferences and gear deployment patterns (Bigelow *et al.* 1999). For purse seine fisheries, effort consists of fishing days by set type (associated, unassociated). For each non-longline fishery, a grand mean effort value is computed over all periods and regions of activity. Normalized effort by region, month, and fishery are obtained by dividing effort in each stratum by the grand mean. All longline fishery effort was normalized simultaneously.

Gear selectivity

Selectivity patterns are length-specific, and largely mirror those reported by Hampton and Fournier (2001). Non-longline selectivities are modelled as compound distributions, and do not always increase or decrease monotonically. A logistic relation is used to compute longline selectivity patterns

$$(21) \quad S_i = \left(1 + \exp \left\{ - \frac{i - c_1}{c_2} \right\} \right)^{-1}$$

Parameter c_1 and c_2 are set to 104.49 and 10.18 for fishery 10, and 112.69 and 3.86 fisheries 11-16. Unless specified otherwise for certain tests, all selectivity patterns are constant though time with no stochastic variation.

Catchability patterns

Fishery-specific baseline catchability rates are initially chosen to produce catch trends similar to those observed during 1962-98. These can then be further adjusted to exhibit temporal and stochastic variation to account for efficiency gains, changes in environmental conditions, or random variation in catch rates. The formulation used is

$$(22) \quad \varepsilon_{vt} \sim N(0, \sigma_q^2)$$

$$(22) \quad q_{vt} = c_{vt} h_{vt} q_v e^{\varepsilon_{vt} - 0.5\sigma_q^2}$$

Temporal increases in catchability are obtained by setting c_{vt} using any user-specified function (default = 1.0). Longline catchabilities vary seasonally as reported by Hampton and Fournier (2001). For fisheries in northern zones 1-2, catchability increases progressively until June, and decreases until December. The amplitude of the change is $\pm 33\%$ of the rates in March and September. Longline fisheries in southern zones 6-7 follow the opposite pattern. Both cycles are obtained by letting h_{vt} vary from 0.67 to 1.33 during the year for $v = 10, 11, 15, 16$. The default value for σ_q is 0.0 (no error), but for simulations requiring noise in the fishing effort versus fishing mortality relation, σ_q is set to $q/10$ for all fisheries.

Exploitation process

Fishing and total mortality rates are computed as instantaneous rates using the conventional form of the catch equation (Gulland 1983). Numbers by age category are sequentially converted to numbers-at-length before length-specific mortality rates are applied, and the model keeps track of survivors and catches by age and length category. The same procedure is applied to tagged fish.

$$(23) \quad F_{vt} = q_{vt} f_{vt}$$

$$(24) \quad F'_{it} = \sum_{v=1}^V F_{vt} S_{iv}$$

$$(25) \quad Z_{ijt} = F'_{it} + M_{jt}$$

$$(26) \quad N_{jt+1} = \sum_{i=1}^I N_{ijt} e^{-Z_{ijt}}$$

$$(27) \quad C_{ijt} = \frac{F'_{it}}{Z_{ijt}} (1 - e^{-Z_{ijt}}) N_{ijt}$$

$$(28) \quad C_{ijvt} = \frac{F_{vt} S_{iv} C_{ijt}}{F'_{it}}$$

Catch sampling

Random samples of catches by age and size category for each fishery/time/area stratum can be generated for any user-defined sampling rate, or to match the sample sizes in the OFP database. Catches are rarely sampled systematically, so sample variability tends to exceed that of the catches. The simulator adds observation error by randomly sampling 10% of the catch frequencies, and multiplies each frequency by 10. This procedure complies with the MFCL default assumptions concerning sample variation.

Tag release-recapture data

The 40,000 yellowfin tagged in the WCPO during the 1989-92 operations (Kaltongga 1998) are used to compute recovery patterns. Each tagged fish is assigned a sex at random, an age at random from the probability distribution of age-at-length, and linked to a school with the same sex, age and release stratum. From there onwards, the tagged fish are subject to the same biological processes affecting the school to which they are assigned. Uniform random deviates are generated for each tag recapture. The tag is reported if the deviate is less than fishery reporting rate (user-specified, or as reported by Hampton and Fournier 2001). For each reported tag, a length-at-release is obtained by randomly sampling without replacement from the corresponding release record.

Total biomass trends and ratios

Average biomass during first and last three quarters of the simulation period are computed from the time series generated with and without exploitation. From these, two biomass ratios are computed for comparative purposes

$$(xx) \quad B_t = 0.001 \sum_{i=1}^I \sum_{w=1}^W w N_{it} P_{wi}$$

$$(xx) \quad B_t^* = 0.001 \sum_{i=1}^I \sum_{w=1}^W w N_{it}^* P_{wi}$$

$$(xx) \quad Q_1 = \frac{\sum_{t=435}^{444} B_t}{\sum_{t=1}^9 B_t}$$

$$(XX) \quad Q_2 = \frac{\sum_{t=435}^{444} B_t^*}{\sum_{t=435} B_t}$$

Yield analysis

The procedure used is described by Hampton *et al.* (2003), after Shepherd and Pope (2002). A yield curve is generated by first computing the average F-at-age over the 36 months prior to the last year. An abundance-per-recruit index is then computed for multiples (x) of the baseline mortality rates

$$(xx) \quad \phi_a(x) = 1.0 \quad ; \quad a = 2$$

$$(xx) \quad \phi_a(x) = \exp\left[-\sum_{a=3}^A (M_a + x\bar{F}_a)\right]; \quad 2 < a \leq 84$$

Age-specific mean weights and proportions-at-maturity are used to compute indices of biomass-per-recruit, spawning biomass-per-recruit, and equilibrium biomasses

$$(xx) \quad \Phi = \sum_{a=2}^A \phi_a(x) \bar{W}_a$$

$$(xx) \quad \Phi^S = \sum_{a=2}^A \phi_a(x) \bar{W}_a \Gamma_a$$

$$(xx) \quad \tilde{B}(x) = \tilde{R}(x) \Phi(x)$$

$$(xx) \quad \tilde{B}^S(x) = \tilde{R}(x) \Phi^S(x)$$

Assuming the stock-recruitment parameters (α , β) are time-invariant and hold over a biomass range, after some substitutions, equilibrium values can be computed from

$$(xx) \quad \tilde{R}(x) = \frac{\alpha \tilde{B}^S(x)}{\beta + \tilde{B}^S(x)} = \alpha - \frac{\beta}{\Phi^S(x)}$$

$$(xx) \quad \tilde{B}^S(x) = \alpha \Phi^S(x) - \beta$$

$$(xx) \quad \tilde{B}(x) = \alpha \Phi(x) - \beta \frac{\Phi(x)}{\Phi^S(x)}$$

$$(xx) \quad \tilde{N}_a(x) = \tilde{R}(x) \phi_a(x)$$

$$(xx) \quad \tilde{C}_a = \frac{\bar{F}_a}{M_a + \bar{F}_a} \tilde{N}_a(x)$$

$$(xx) \quad \tilde{Y}(x) = \sum_{a=2}^A \tilde{C}_a(x) \bar{W}_a$$

Let z be the value of x corresponding to the maximum yield. PRPs are then obtained from

$$(xx) \quad B_{MSY} = \tilde{B}(z)$$

$$(xx) \quad B_{MSY}^S = \tilde{B}^S(z)$$

$$(xx) \quad F_{MSY} = \frac{\tilde{Y}(z)}{\tilde{B}(z)}$$

Statistical conversions

The simulator's monthly-based statistic must be converted to MFCL formats to conduct analyses and compare results. Catch, effort, size frequencies and yields are pooled by quarter, and numbers by monthly age classes 2-84 are converted to numbers by 20 quarterly age classes, with the last one including fish > 60 months of age (i.e. a 'plus' group). Recruitment per quarter includes all fish of monthly ages 2-4 at the start of each quarter. Natural mortality rates by quarterly age class are first computed under equilibrium conditions, with constant recruitment and no fishing mortality. Approximate values for time-series of F by quarterly age class during the exploitation phase are then derived from these. For instance, let q1 denote a quarter, fishing mortality on the recruits (r) during the first quarter (up to $t=4$) is approximated from

$$(xx) \quad \tilde{M}_{r,q1} = -\ln \left(\frac{\sum_{a=5}^7 \tilde{N}_{a,q2}}{\sum_{a=2}^4 \tilde{N}_{a,q1}} \right)$$

$$(xx) \quad F_{r,q1} = -\ln \left(\frac{\sum_{a=5}^7 N_{a,q2}}{\sum_{a=2}^4 N_{a,q1}} \right) - \tilde{M}_{r,q1}$$

TABLES

Table 1. Source of information used to configure the simulator of the yellowfin tuna fishery in the WCPO. Only major sources listed.

Model component	Known	Estimates	Hypothesis	Variability source	Information source
Growth patterns		X		process error	OFP studies
Length-at-age		X			OFP records
Weight-at-length		X			OFP records
Length-at-weight		X			OFP records
Maturation rates			X		Literature survey
Egg production		X		environmental	Literature survey
Recruitment trend			X	log-normal	MFCL analysis
Natural mortality		X			MFCL analysis
Oceanic conditions			X		OFP studies
School movement			X	random walk	Tracking studies
Fish distribution	X				Literature survey
Catchability coefficients		X		process error	Literature survey
Gear selectivity		X		process error	MFCL analysis
Effort distribution	X				Literature survey
Catch composition	X				Literature survey
Tag releases	X				OFP studies
Tag reporting		X		observation error	OFP studies
Error structures			X		Literature survey

FIGURES

YFT FISHERY OPERATIONAL MODEL STRUCTURE

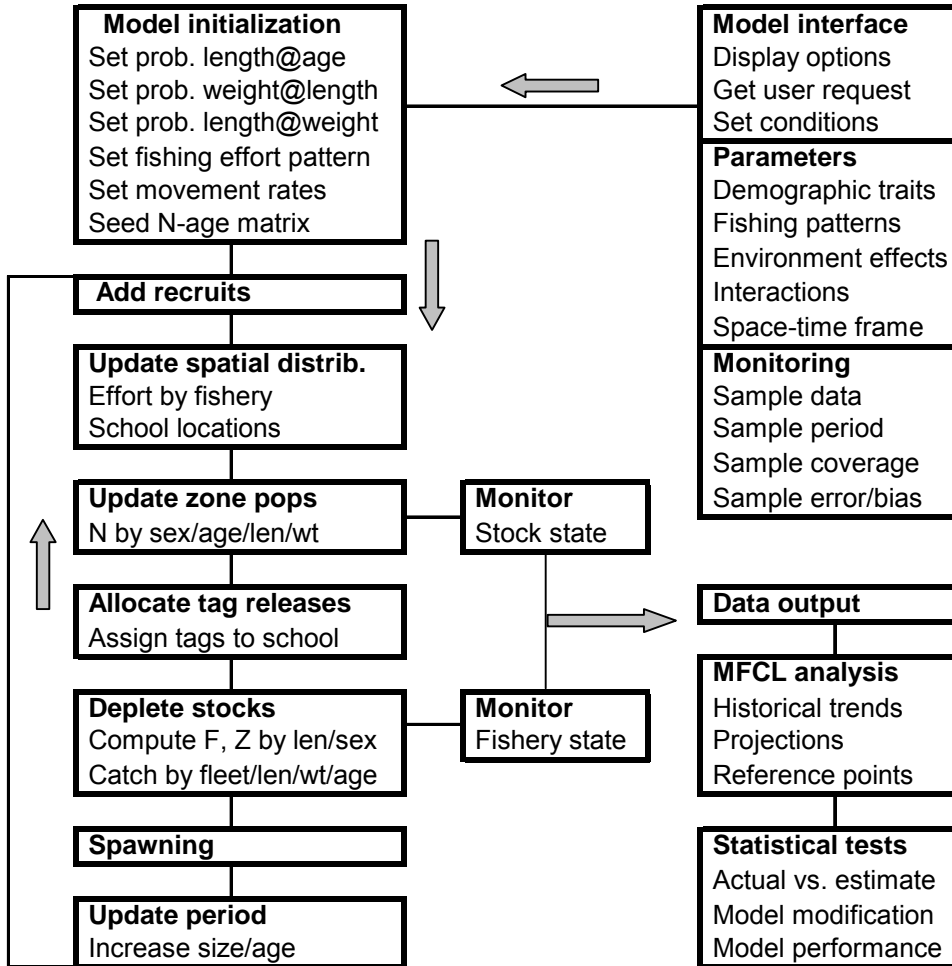


Figure 1. Structure of the simulator and procedure used to generate data and evaluate the performance of stock-assessment models

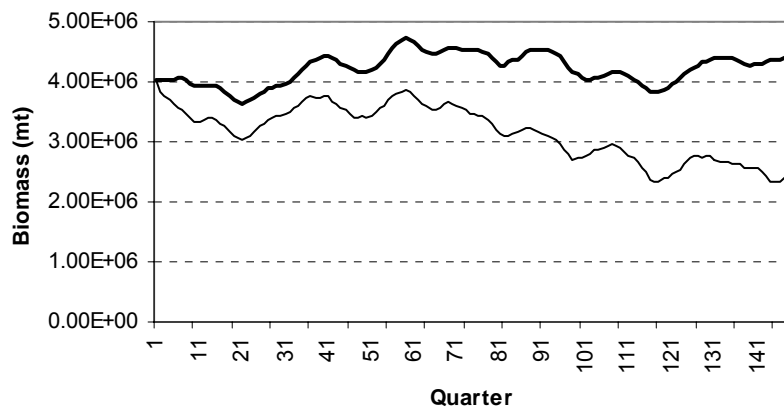


Figure 2. Predicted trends in total biomass by quarter, in the absence of exploitation (thick line), and in the presence of exploitation (thin line). without sex-specific adjustments. Starting value corresponds to B_0 . Final value are labelled B_{end} (thick line), and B^*_{end} (thin line).

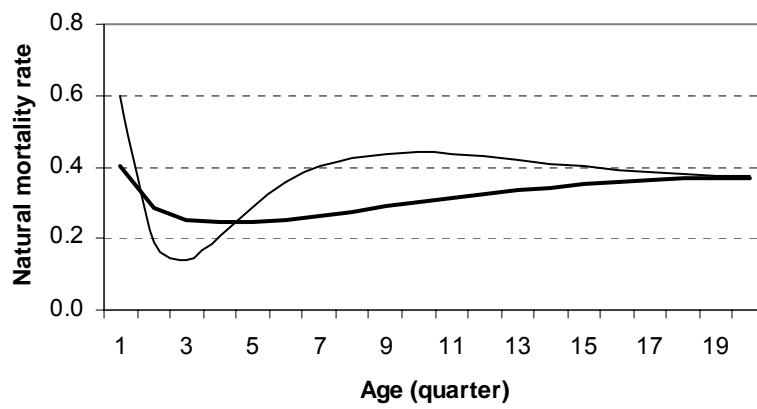


Figure 3. Simulated trends in M-at-age by quarter, without sex-specific adjustments. Thin line depicts hypothesized yellowfin mortality pattern (type_1). Thick line depicts an alternative pattern arbitrarily chosen for testing purposes (type_2).

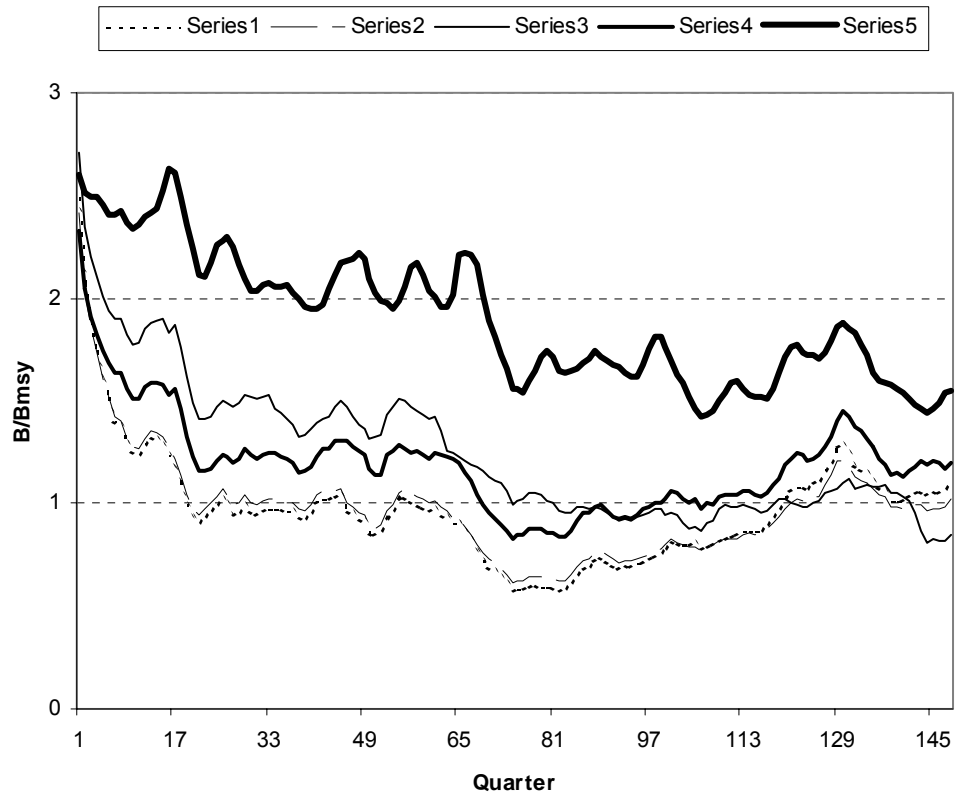


Figure 4. Simulated time series in total biomass levels relative to B_{msy} , for scenarios 1-5. The trends are crude indicators of the impact of fishing on the population for the first realisation of each scenario.

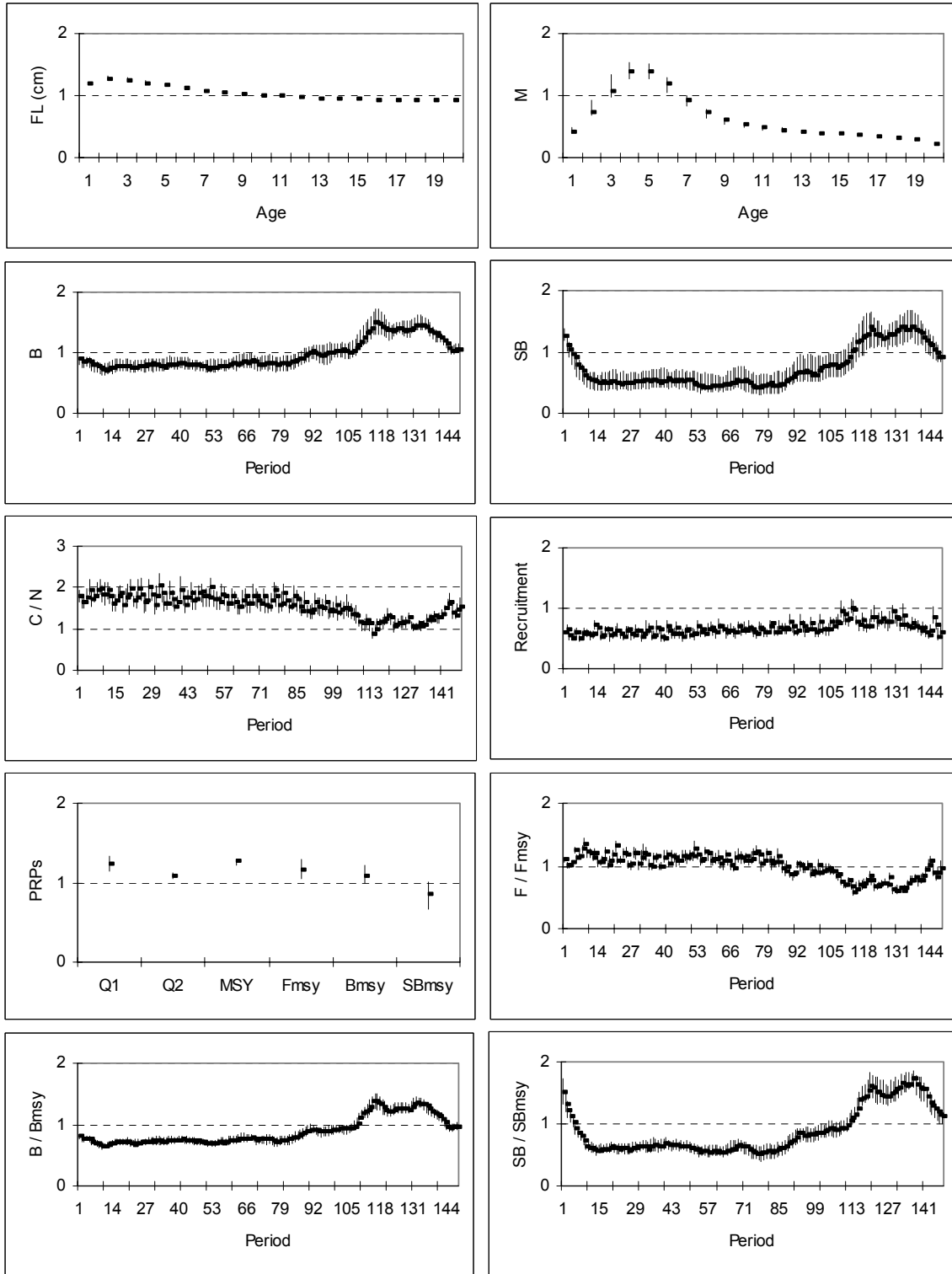


Figure 5. Result summary for scenario 1. Vertical bars indicate inter-quartile range of estimate/actual values over all realizations. Labels are fork length (FL), natural mortality (M), biomass (B), spawning biomass (SB), exploitation rates (C/N), reference points and indicators (PRPs), F-ratio and B-ratios. See Appendix A for definitions.

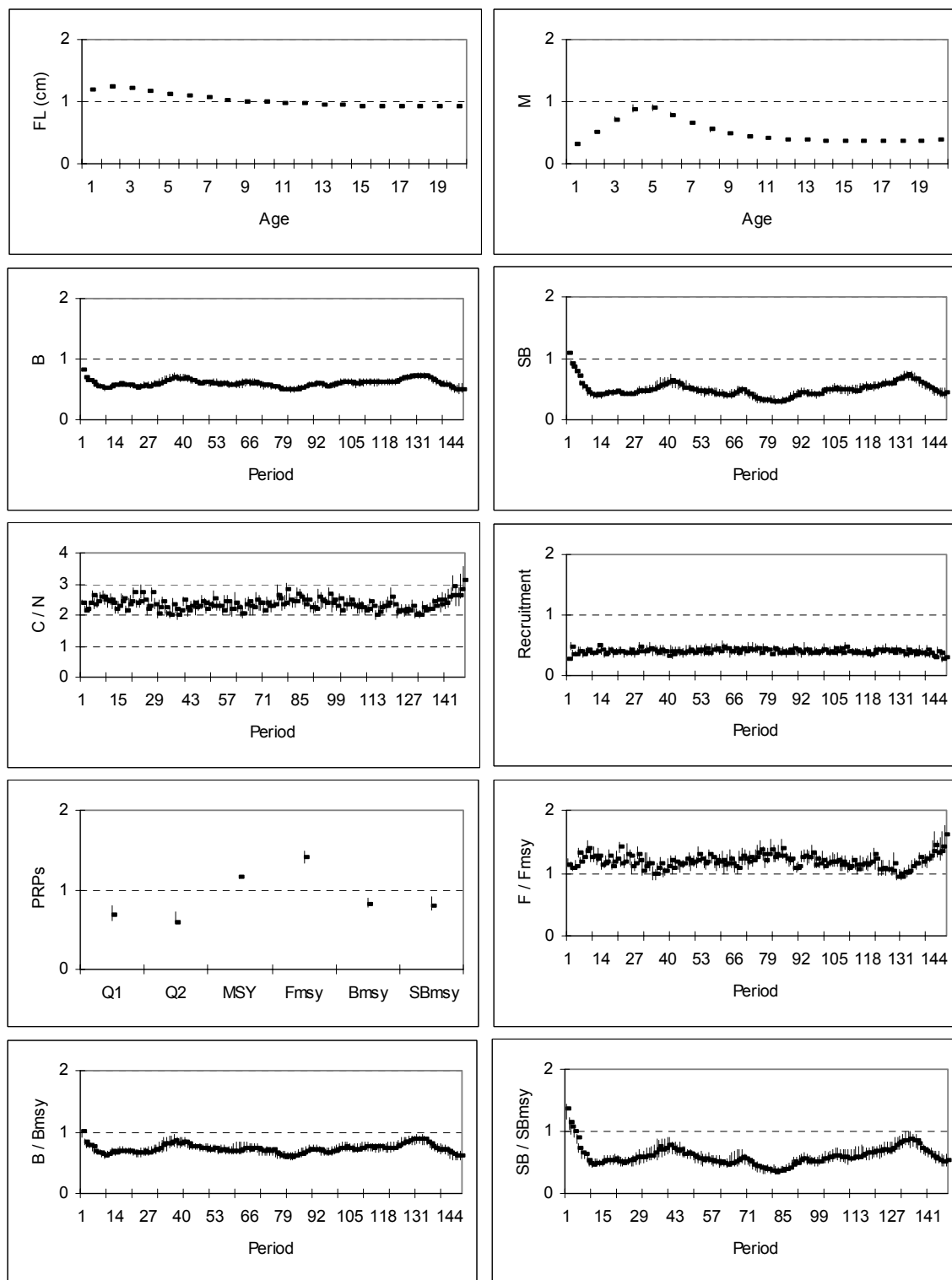


Figure 6. Result summary for scenario 2. Vertical bars indicate inter-quartile range of estimate/actual values over all realizations. Labels are fork length (FL), natural mortality (M), biomass (B), spawning biomass (SB), exploitation rates (C/N), reference points and indicators (PRPs), F-ratio and B-ratios. See Appendix A for definitions.

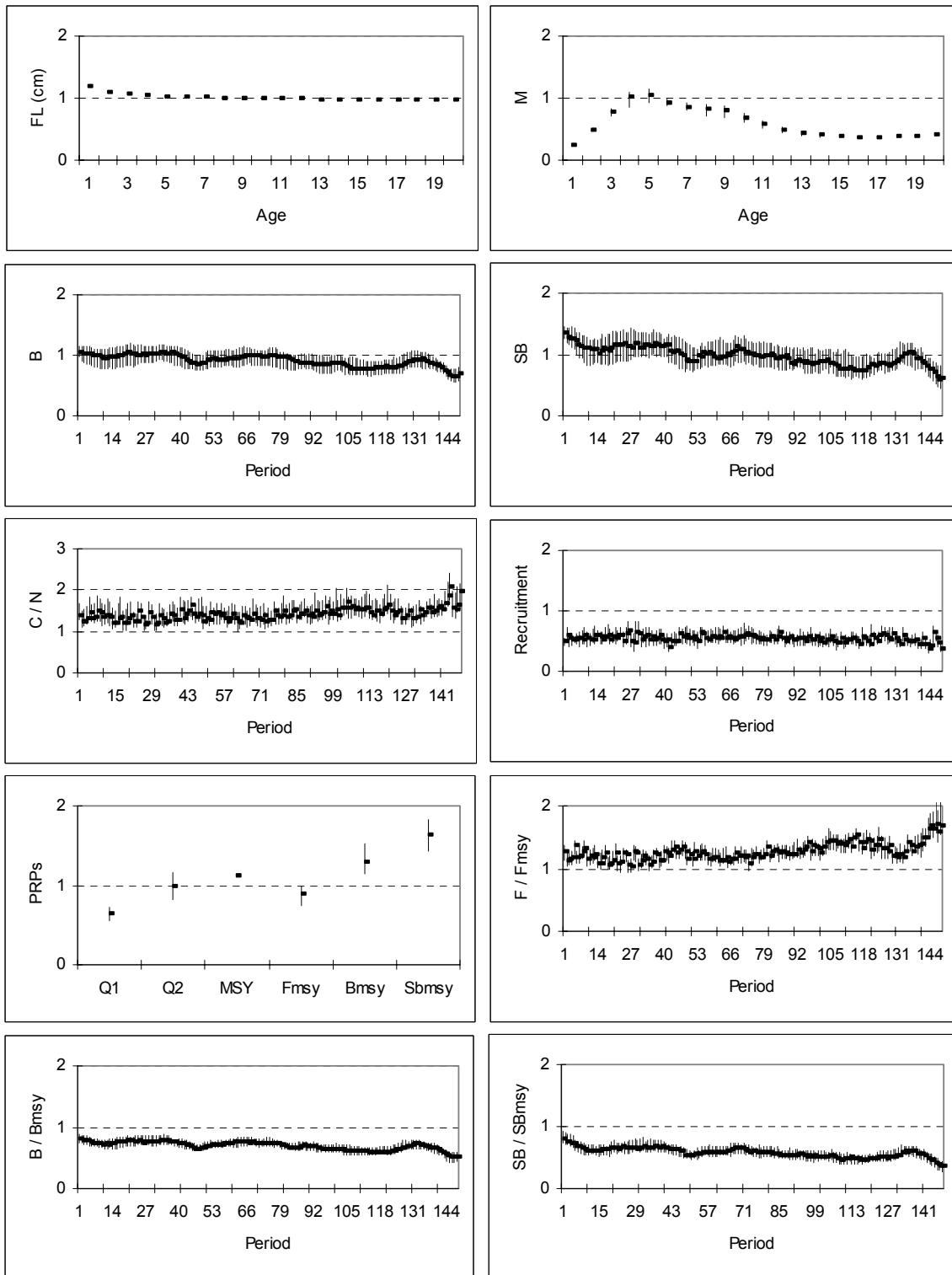


Figure 7. Result summary for scenario 3. Vertical bars indicate inter-quartile range of estimate/actual values over all realizations. Labels are fork length (FL), natural mortality (M), biomass (B), spawning biomass (SB), exploitation rates (C/N), reference points and indicators (PRPs), F-ratio and B-ratios. See Appendix A for definitions.

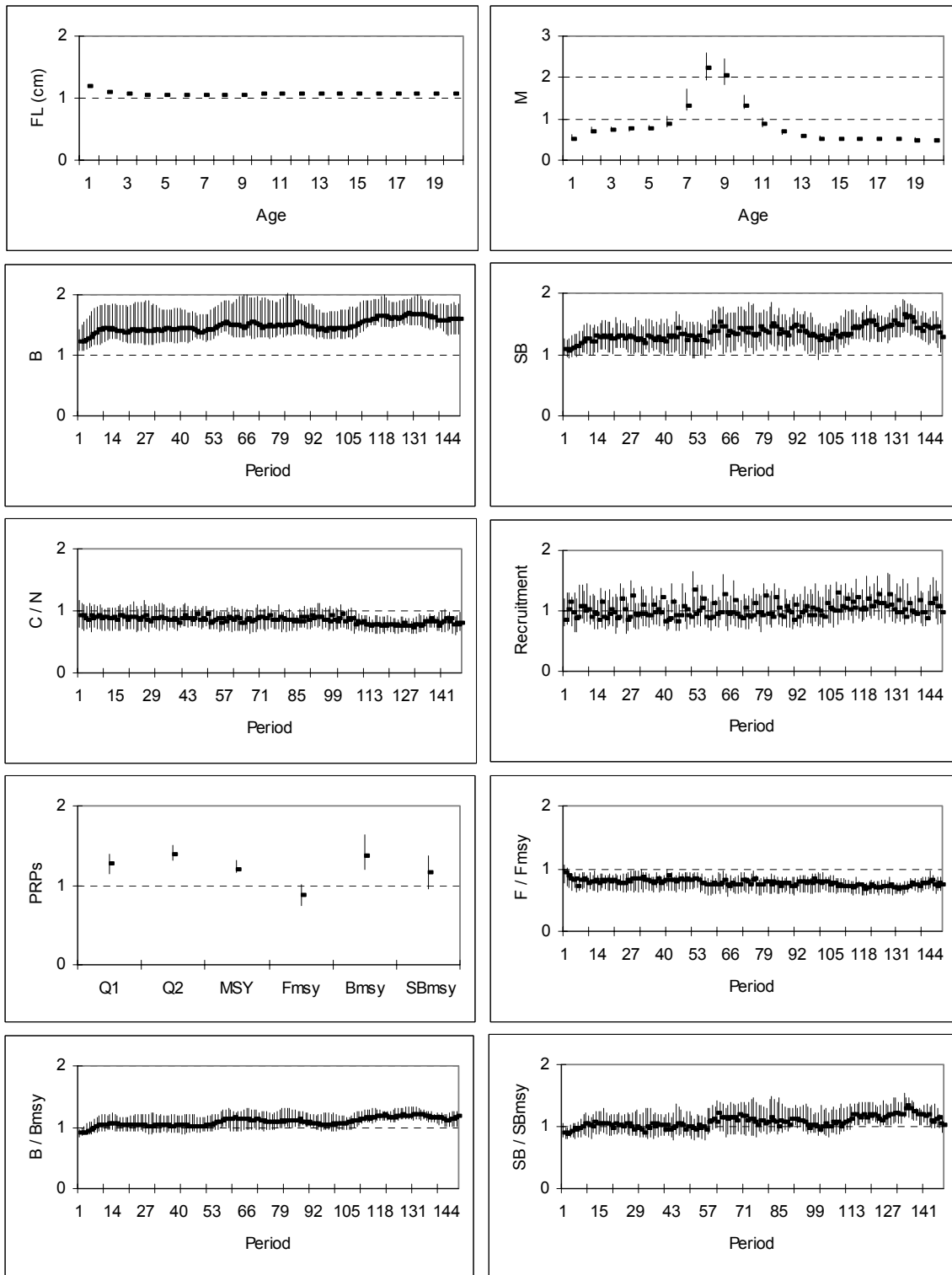


Figure 8. Result summary for scenario 4. Vertical bars indicate inter-quartile range of estimate/actual values over all realizations. Labels are fork length (FL), natural mortality (M), biomass (B), spawning biomass (SB), exploitation rates (C/N), reference points and indicators (PRPs), F-ratio and B-ratios. See Appendix A for definitions.

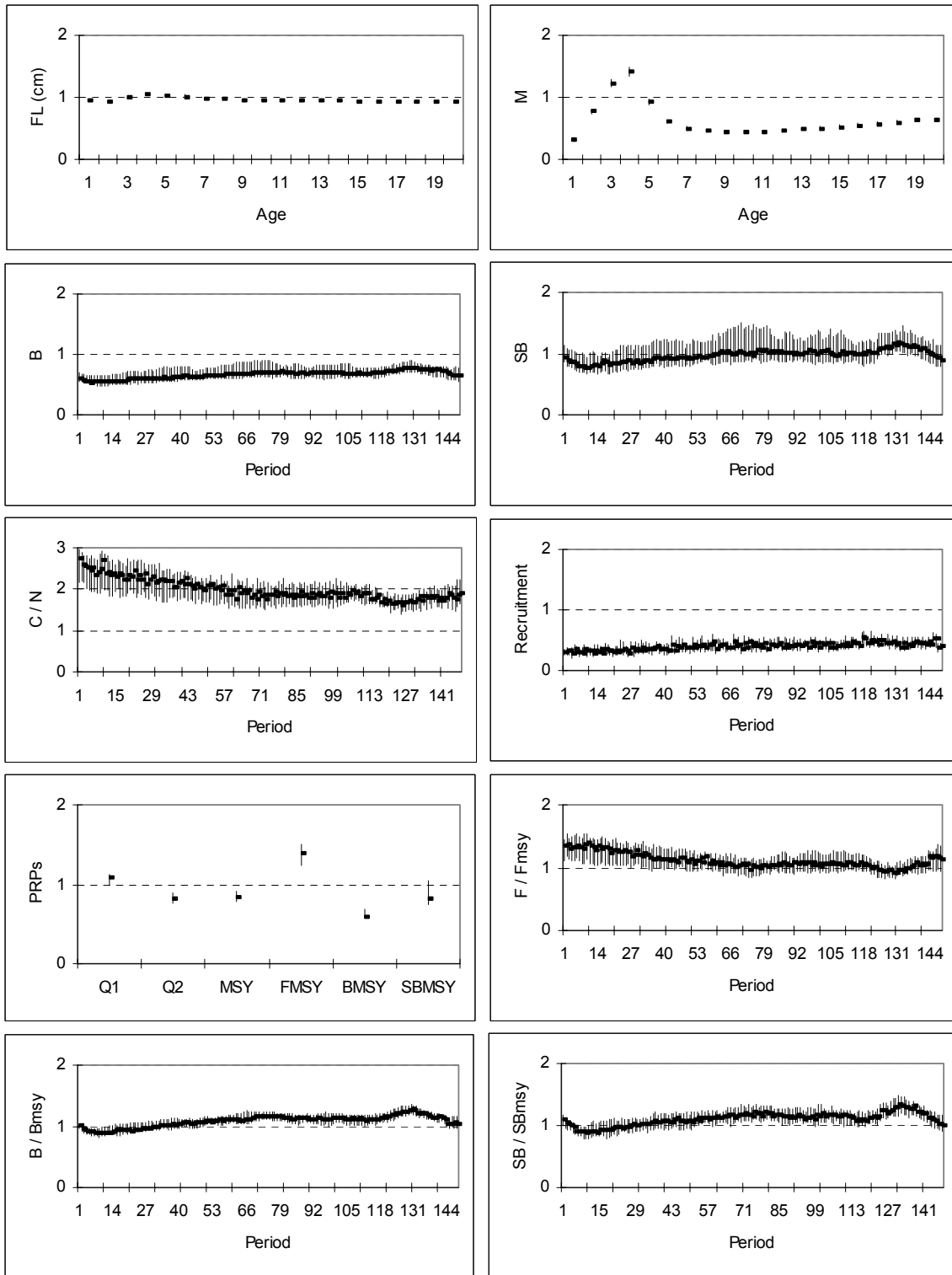


Figure 9. Result summary for scenario 5. Vertical bars indicate inter-quartile range of estimate/actual values over all realizations. Labels are fork length (FL), natural mortality (M), biomass (B), spawning biomass (SB), exploitation rates (C/N), reference points and indicators (PRPs), F-ratio and B-ratios. See Appendix A for definitions.