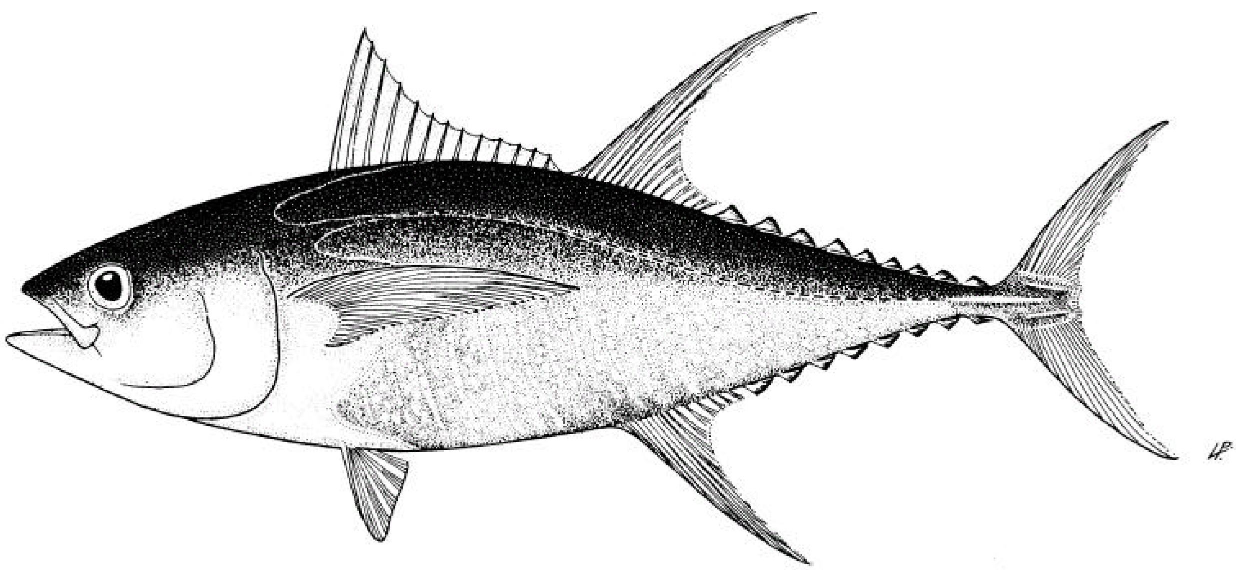
SCTB15 Working Paper

MWG - 1

Testing the accuracy of MULTIFAN-CL assessments of the WCPO yellowfin tuna fishery conditions



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Introduction

The application of the precautionary approach, advocated by the United Nations Straddling Stock Agreement (U.N. 1995), requires that fishing nations establish and use Precautionary Reference Points (PRPs) for fishery management purposes. These points are estimated values that correspond to the state of the resource and the fishery. Management agencies usually make a distinction between two types of precautionary reference points. There are limit reference points and target reference points. Limit reference points set boundaries that are intended to constrain harvesting within safe biological limits, within which the population can produce maximum sustainable yield. Target reference points are intended to meet management objectives (ICES, 1996).

Several reference points were proposed over the past decade (FAO 1993). The merits of some points have been investigated (Anon. 1993), and many fishery management agencies formulate plans using specific reference points (Restrepo et al. 1998, Boggs et al. 2000). A cursory review of the literature suggests that no single reference point is superior in all contexts. For straddling and highly migratory stocks, reliance on F-based reference points can be problematic when there are large year-to-year changes in effort, and the resource is subject to uneven exploitation rates in different areas. Since fishing mortality rates are often derived from estimates of biomass and fishery removals, some investigators prefer control policies based directly on catch or biomass (Richards et al. 1998). Consequently, identifying the most appropriate reference point involves consideration of factors such as data availability, fishery complexity, stock dynamics and management objectives (Anon. 1993).

Once appropriate points have been identified, the analytical procedures used to assess the fishery and stock conditions must be able to provide estimates of the points desired. During the last decade, the Oceanic Fisheries Program (OFP) of the Secretariat of the Pacific Community (SPC) has invested considerable resources into the development of an age-structured, length-based, statistical catch-at-age model (MULTIFAN-CL, or MFCL for short) to help assess the status of pelagic fish stocks in the WCPO (Fournier et al. 1998). More recently, specialised extensions were added to MFCL to estimate reference points. As noted by Richards et al. (1998), by integrating the assessment and forecasting operations into a single modelling framework, one should be able to obtain confidence intervals that account for more of the uncertainties in underlying processes (Fig. 1).

During the 18 months, an investigation was conducted to determine the reliability of the MFCL estimates under various conditions concerning fishery complexity, stock dynamics, survey design, measurement and reporting errors, and survey limitations. This was accomplished by using an operational model (Linhart and Zucchini, 1986) to generate pseudo-observations using 'known' parameter values, and then comparing these to the MFCL estimates obtained from the analysis of the same observations. As noted by Hilborn and Walters (1992, p. 239), the use of operational models should be an integral part of any stock-assessment. This approach has been used by NMFS for swordfish assessments (Goodyear 1989, Labelle 1999), by fishery scientists from the Commonwealth

Scientific and Industrial Research Organisation (CSIRO) to provide tuna fishery management advice (Campbell et al. 1998), and by stock-assessment review committees in Europe and in North America (ICES 1993, NRC 1998).

The latest version of the operational model contains 3500 lines of C++ code (excluding numerical libraries), and runs as a console application on several platforms (PC/NT, PC/Linux, Mac/OS9), with commonly available compilers (Borland, Metrowerks, MSVC6, etc.). The model is designed mainly to simulate key aspects of the dynamics of the WCPO yellowfin fishery, as described in Hampton and Fournier (2001). The model includes components for recruitment, growth, natural mortality, spawning, fish movement, and exploitation by up to 16 fisheries with different gear types and selectivity patterns. (Table 1). All commercial effort series available to SPC are used to represent the historical and spatial trends in exploitation patterns. The model also makes use of data from tagging programs conducted by SPC staff in the WCPO, and predicts the expected tag recovery patterns in various time/area/fishery strata. The model can generate a wide variety of outputs on key components of the fisheries or the stock, given user specified levels of process and observation errors. This paper describes the main features, structure, underlying hypotheses and limitations of the latest version of this model. The testing procedure used and the results of tests conducted so far are also described. In the following sections, the operational model is referred to as the simulator, to help distinguish it from other models referred to in the text.

Symbols and notation

i	= index denoting a 2cm length category (range: 1-100, I=max.)
a	= index denoting an age group (in months, range: 1-84, A=max.)
w	= index denoting a 1 kg weight category (range: 0-200, W=max.)
s	= index denoting the sex category (male = 0, female = 1)
y	= index denoting a calendar year (range: 1-37, Y=max.)
t	= index denoting the month of the year (range: 0-12)
v	= index denoting a fleet or fishery (range: 1-16, V=max.)
x_i	= mid-point on the 2 cm length interval of the ith category
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) parameter for maximum growth rate per year
G_a	= growth rate reduction coefficient, age a
ρ	= 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	= catchability coefficient
S_{vi}	= gear selectivity, fleet v, on fish in length interval i
E	= egg production
R	= number of recruits
V	= fish movement rate due to swimming (km $\cdot$ d^{-1})
D_i	= distance (in km) travelled in a day, by a fish in length category i
T	= time interval (in days)
Γ_i	= proportion of fish in length interval i that are mature
ϕ_i	= fecundity of length i female
∇	= sea surface temperature gradient index for adjacent regions
ε	= random error term ~ $N(0;\sigma_\varepsilon^2)$
ω	= residual deviation
b_n	= generic model coefficients
SST	= sea surface temperature
SOI	= southern oscillation index

Model components

Spatial and temporal resolution

The spatial coverage of the model is 40 ^{o}S - 40^{o}N, and 110 ^{o}E - 150 ^{o}W, which includes most of the WCPO. The area is split into a grid of 320 regions covering areas of 5^{o}X5^{o} in longitude and latitude. Marginal regions and those covering land are omitted, so only 237 regions are used in the model. The time span covered by the model is 1962-98, using one-month iteration steps, which provide a temporal resolution of 444 periods.

The yellowfin population is composed of 237 stocks, defined on the basis of the region of recruitment. The maximum longevity for this species is set to 84 months. The model initially builds-up the population in a deterministic fashion without exploitation for the first few years until an equilibrium state is reached. Stochastic processes are then enabled, and the population is subject to exploitation for 37 years, by up to 16 fisheries, each operating in one of seven fishing zones. The number of regions covered by each zone is 18-62. Exploitation is modelled by sequentially applying the combined fishing effort for all fisheries in a month, region and size category to each age class of each stock in the corresponding time/area stratum.

Growth

Lehodey and Leroy (1999) used von Bertalanffy equation to describe growth in this species. The authors adjusted the model to account for a growth reduction in early life. A similar adjustment was made to the re-parameterised version of the von Bertalanffy model proposed by Schnute and Fournier (1980). Examination of length-at-age data suggested that a curvilinear relation between the standard deviations and means in length-at-age that is best expressed by a quadratic function, but the user can specify parameter values that correspond to a linear function between both variables so as to meet the assumptions of MFCL. The modified functions, once fitted to the data, are used to compute the probability of age a fish being in each length interval.

(1) $$G_a = \frac{b_0}{s\sqrt{2p}} \exp\left\{ \frac{-(a - a^*)^2}{2s^2} \right\}$$

(2) $$r_a = \exp(-K + G_a)$$

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

(4) $$s_{L,a} = b_1 + b_2 u_{L,a} + b_3 u_{L,a}^2$$

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

With age expressed in months since birth, the parameter values for males are A=84, L_1=15.445, L_A=140.896, K=0.073, a*=10.721, σ=4.575, and b_0=0.288 for males. For females, A=84, L_1=19.573, L_A=153.032, K=0.556, a*=10.362, σ=3.639 and b_0=0.152. Using length-weight data for both sexes combined, the quadratic function parameter estimates b_1, b_2 and b_3 are -6.121, 0.325 and -0.002. Alternatively, if one assumes a linear function exists between the variables, the best fitting values obtained were 6.140, -0.009 and 0.000 respectively. Probabilities are computed for the 0-200 cm range, by 2-cm intervals (0-1.99 cm = 1 cm cat. = index 1).

Weight-at-length

Examination of 16,000 length-weight measurements extracted from the OFP database suggests 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 two relations are used to compute the probability that fish in length interval i are in weight interval w, under the assumption that the weight-at-length distribution is normal. Probabilities were computed for the 0-200 kg range, by two kg intervals (0-0.99 kg = 0 kg cat. = index 0).

(6) $$m_{W,i} = 0.000017593 l^{3.0}$$

(7) $$s_{W,i} = 0.1485 + 0.0972\ m_{W,i}$$

(8) $$P_{wi} = \frac{1}{s_{W,i}\sqrt{2p}} \exp\left\{\frac{-(x_w - u_{W,i})^2}{2 s_{W,i}^2}\right\}$$

Length-at-weight

The relation between fork length and total weight also conforms to a power function, and the standard deviation to mean relation in length-at-weight is linear over the range of observations. The two relations are used to compute the probability of fish in weight category w being in length category i, under the assumption that the length-at-weight distribution is normal. Probabilities are computed over the 0 -200 kg range, by two kg intervals (0-1.99 kg = 1 kg cat. = index 1).

(9) $$m_{L,w} = 38.552 w^{0.334}$$

(10) $$s_{L,w} = 4.0930 - 0.0009\ m_{L,w}$$

(11) $$P_{iw} = \frac{1}{s_{L,w}\sqrt{2p}} \exp\left\{\frac{-(x_i - u_{L,w})^2}{2 s_{L,w}^2}\right\}$$

Natural mortality

Yellowfin are thought to be subject to high natural mortality in early life, which decreases until the onset of maturation, then increases again up to about 135 cm. Beyond this size, M decreases again due to the attrition of females subject to higher mortality rates (Anon 2000, Hampton and Fournier, 2001). A cubic function is used to model the relation between natural mortality and fork length for males and females separately.

(12) $$M_i = b_0 + b_1 i + b_2 i^2 + b_3 i^3$$

The parameters values used for males are 9.548422, -0.334335, 0.003979 and -0.000014 respectively. The values for females are 14.94001, -0.50767, 0.005696, and -0.0000195. The predicted trends in M-at-length tends to be higher for females, and conform well to the estimates of Hampton and Fournier (2001). The mortality rates translate into slightly higher male:female ratios in the 50-100 cm range, as observed in longline catch samples (SPC, unpublished records).

Spawning activity

Plankton surveys and gonad inspections indicate that yellowfin spawn year-round across the Pacific in waters with SSTs of 24-32 ^{o}C, with most spawning activity occurring east of 150 ^{o}W, inside the 5 ^{o}S-30 ^{o}N band. On average, mature females are considered to spawn every second day. In the latest version of the model, it is assumed here that all mature females spawn, there is no shortage of males, no competition for mates or Allee effects at low densities (Allee et al. 1949). A logistic equation is used to predict the proportion-at-maturity of females by length category, and a power function is used to predict batch fecundity from fork length. These two functions can be used to compute an egg production index for a period given the number of females by length category

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

(14) $$f_i = 0.2934\, i^{3.2673}$$

(15) $$E_t = \sum_{i=1}^{I} N_{it} \Gamma_i f_i$$

Here again, the user can substitute the above functions by others that conforms more strictly to the assumptions of MFCL. For most of the MFCL test conducted, the proportions at maturity for both sexes are simply set to 0% for ages 2 -39, 50% for ages 40-45, and 100% for older ages.

Recruitment

Current plans are to use a stochastic version of the Beverton-Holt stock-recruitment model to predict recruitment at each time step. However, the latest version of the model does not yet link recruitment and to egg production. Instead, the number of 60 day old recruits added to the population each month is considered to be a random, log-normal variate centred on a mean value of about 4E+07, with a user-specified coefficient of variation, and a 50:50 sex ratio at recruitment.

(16) $$R_t = \overline{R} \cdot \exp(e - 0.5s_e^2)$$

Juveniles (12-30 cm) have been found in the WCPO between 23°S and 30°N, and over a narrower latitudinal range eastward (Suzuki 1994, Itano 2001). The model reproduces this pattern by distributing recruits across regions with increasing sea surface temperatures (SST) exceeding 25°C (Itano, 2001). Average monthly SSTs were deduced from an ocean circulation model (see Chai et al., 2001, Dugdale et al. 2001). The recruits were not distributed uniformly across all the suitable regions. Instead, the fraction of the total recruitment each region received is linked to its longitudinal proximity to Papua New Guinea (PNG). Proportions were lowest at 150W, increased progressively up to PNG, and decreased progressively up to 110E. As a results, recruitment to regions around PNG (140-145E) are about 10 times the level of those at the eastern end of the WCPO (150W).

Movement

All fish recruiting to a region/month stratum are considered to form a 'school', and remain together until they die, at most 82 months later. Based on the historical SST pattern, the model can add 150-237 schools to the population each month, and can keep tract of the location of about 17,000 schools each month. Tagging studies have not yet shown that yellowfin exhibit regular movements or migration patterns, so school movement is modelled a two dimensional random walk. Brill et al. (1999) showed that yellowfin swimming speed could be predicted from fork length. The linear relation proposed by the authors is suitable for the observed size range (50-170 cm FL), predicts unrealistic speeds for small yellowfin (<30 cm). A more plausible relation was obtained by fitting an exponential function to these data. This relation is used to compute the distance yellowfin in a size category can potentially travel in a day. The probability of moving in one direction relative to an initial position is assumed to be a binomial process. The probability that a fish will be (x) km from its initial position at the end of the month (T = 30) is computed using the normal approximation to the binomial

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

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

Assuming there is equal probability of moving east or west in each period (p = 0.5), a 100 cm yellowfin is predicted to travel about 83 km per day, and there is a 0.05 probability that this fish would end up >750 km west of its original location one month later if it was limited to east-west movement. This equation is used to determine the north-south displacements. The location of each fish school is tracked by sequentially computing possible displacement vectors at random, using the transformation method described by Press et al. (1992, p. 201). A cumulative probability distribution is first produced from Eq.18 using the expected mean length-at-age for a school. This distribution forms a length-specific definite-integral curve with probabilities ranging from 0 to 1, associated with distances of ±3000 km. To determine the possible displacement of a school in a month, two uniform random deviates are generated, and the corresponding distances on the definite-integral curve are taken as those travelled from the last location, with negative values representing locations to the south and east respectively. This yields two displacement vectors, with displacements in each plane equal to half of the value of each random deviate. Distances between the centre of adjacent regions are determined, and the school is moved to the new region if the displacement exceeds the centre to centre distance. When the displacement is not sufficiently large to move to another region, it is added to the predicted displacement of the next monthly time step.

Factors like SST and ENSO events are know to affect tuna distribution (Lehodey et al. 1997). To make movement more realistic, SST gradients and the southern oscillation index (SOI, Chen 1982) are used to condition school movement. Displacements to the west and east are increased during La Nina and El Niño episodes respectively. The SOI values available to SPC for 1962-98 ranged from -4.7 to 7.5, with negative values representing an eastward displacement of the warm pool (see Lehodey et al, 1997). These values were scaled to a range of ± 4.7, and used to adjust displacements by making the probability parameter (Eq. 18) a function of the scaled SOI.

(19) $$p = 0.5 + 0.25\left(\frac{SOI}{4.7}\right)$$ east-west displ.

The SOI index adjustment are applied to schools located within the equatorial band, east of 155^{o} E under La Nina conditions, and between 110-130^{o} E and 160-180^{o} E under El Niño conditions. This allows for the build-up of densities in eastern regions during the first period, and in western periods during the later period. Predicted north-south displacements are simply reduced when schools move to a region with a colder SST. An SST gradient index is computed for all north-south displacements, except between regions with SST >26^{o}C. (index = 1), when movement is towards a region with an SST <22^{o}C (index = 0), or when the temperature differences >5^{o}C (index = 0).

(20) $$\nabla = 1.0 - \left(\frac{SST_1 - SST_2}{5.0}\right)$$ north-south displacement

A north-south displacement multiplied by this index yields the adjusted north-south displacement. Reductions in predicted north-south displacements are added to the east-west displacements, so that the total distance travelled amounts to the sum of the two displacement vectors. Because of this adjustment, school movement is modelled as a mixture of biased and unbiased random walks (Fig. 2). Examination of the resulting movement patterns indicate that they conform to field observations (Fig. 3), with some schools making extensive east-west migrations, others staying within a few hundred miles of their recruitment area, and with a tendency for east-west displacements to exceed north-south displacements (Suzuki 1994).

Fishing effort

Time series of fishing effort by strata for each of the 16 fisheries were extracted from the OFP database. For fisheries 1-3 (Philippines + Indonesia), nominal fishing effort values were unavailable, so catch levels are used as proxies for effort. For the remaining fisheries (6 purse seine, and 7 longline), standardised effort values (Bigelow et al. 1999, Williams, in prep.) were extracted from the OFP database. For each fishery, a grand mean effort is computed over all periods and regions of activity. Nominal effort values by month/region are then divided by the grand mean to yield time series of normalised effort.

Gear selectivity

The selectivity patterns used in the model are fishery and length specific, and largely mirror those reported by Hampton and Fournier (2001) for domestic and purse seine fleets. For longline fisheries, selectivity-at-length is represented by a logistic relation

(21)
$$S_i = \left(1 + \exp\left\{\frac{b_1 - a}{b_2}\right\}\right)^{-1}$$

The parameter values b_1 and b_2 were set to 104.49 and 10.18 for longline fishery 1, and 112.69 and 3.86 for longline fisheries 2-7. Gear selectivity trends can be held constant throughout the simulation period, or allowed to vary deterministically (progressive change) through time as specified by the user.

Catchability

Catchability rates are arbitrarily set so as to predict observed catches given the selectivity values reported by Hampton and Fournier (2001). This is accomplished by first computing catches using a single low catchability rate for all fisheries. Predicted catches by year/fishery are then divided by the reported catches for the same strata. For each fishery, an overall mean is obtained by averaging the means of over all years of activity, and its inverse is used as a scaling factor. The initial catchability values, multiplied by the scaling factor produce the baseline catchability rates used for predicting catch trends.

Seasonal variation in longline catchability is allowed to match the patterns reported by Hampton and Fournier (2001). For fisheries in northern zones 1-2, catchability increases until June, and then decreases until December. The amplitude of the changes is ± 33% of the baseline rates reached in March and September. For fisheries in southern zones 6-7, the opposite pattern is used. Actual catchability rates by fishery/stratum are computed as follows;

(22) $$q_{vt} = b0_{vt} \cdot b1_{vt} \cdot q_v \exp(e_v - 0.5s_e^2)$$

This formulation allows baseline catchability rates to be constant throughout the simulation period, or allows it to increase progressively (coefficient b0), change seasonally (coefficient b1), add stochastically (exponentiated term) to account for hypothesised gains in efficiency due to learning and technical progress, changes in e nvironmental conditions, or random variation in catch rates.

Exploitation

Fishing and total mortality rates are modelled as instantaneous rates to use the conventional form of the catch equation (Gulland 1983). The fishing mortality formulation used below allows for deviations in the fishing mortality - effort relations (Eq. 23) to meet a key assumption of MFCL concerning stochasticity in the effort series (Hampton and Fournier, 2001). The model converts numbers-at-age to numbers-at-length that are then subject to size-specific Z. The survivors-at-length and catch-at-length are then converted back to catch-at-age and survivors-at-age. Different vessel categories (or fleets) may operate simultaneously in a stratum, so the model accounts for combined impacts. Total catch by length and age categories are dissociated into catch by vessel type based on the contribution of the fleet to the total effective fishing mortality.

(23) $$F_{vt} = q_{vt} f_{vt} \exp(e_v - 0.5s_e^2)$$

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

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

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

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

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

A cursory examination of the predicted catch trends showed that they correspond fairly well with the reported observations for each fishery, in the absence of random variation in effort and catchability (Eqs. 22-23). when all biological processes are operating (Fig. 4).

Catch sampling

The model predicts catches by length, age and weight category by fishery/time/area strata. The model adjusts the number of predicted length frequencies to match those in the OFP database, which are pooled samples obtained from tagging programs, observer programs, port sampling operations, and country submissions. Owing to various constraints, tuna catches are rarely sampled proportionally in each stratum. As a result, catch length frequency variations in the samples exceed those of the actual catches. The simulator accounts for such sampling deficiencies when generating catch length frequencies by taking random samples of lengths for 10% of the actual sample sizes, and then multiplying the final length frequencies by 10. This procedure is in agreement with the underlying assumption of MFCL concerning sample variations.

The model can also generate catch length frequency data according to user-specified sampling rates (1-100%). When this option is selected, the model samples catches across all fisheries, strata and size categories according to the rate specified. Sampling errors and variation in sampling rates can also be modelled if requested.

Tag release-recapture data

The model processes tag release data, and predicts tag recovery patterns. As input, the model uses the RTTP tagging records (Kaltongga, 1998) from activities conducted in the WCPO during 1989-92. The 40,000 or so release records are first aggregated into numbers of tag releases by region, quarter and sex and age. Each tag is assigned to a sex at random. Age-at-release is assigned at random from the sex-specific probability distribution of age-at-length. Tagged fish smaller than the lower bound of the mean length at recruitment are not used by the model. For other release records, the model determines if there is a school present with matching sex and age in the stratum. If a match is found, the tagged group is associated with that school. Each school is assigned a maximum of one tag release, comprising all tagged fish of the same age/sex. If no match is found, a search is conducted for a school in the next oldest or youngest age of the same sex. In odd cases where no match is found, the model tries to assign the tag to a school in an adjacent regions, and tag release records are modified as if tagging had been done in that region. After all search attempts, if no match is found (< 1% of all releases), the tagged group is not included in the simulation.

From the time of release onwards, tagged groups are subject to the same movement, natural mortality and exploitation as untagged fish in the same school. As tags are recaptured, uniform random deviates are generated to categorise them as reported or unreported. If the random number is less than the fishery-specific tag reporting rate (see Hampton and Fournier, 2001), the tag is considered as reported. For each reported recovery, a length-at-release is obtained by randomly sampling (without replacement) from the associated set of length-at-release records.

<u>Output data formats</u>

The model updates the information on the population structure and the fishery each month (Fig. 5), and finally creates five files for analysis and testing. These consist of yft.tag, yft.freq, plot2.rep, diagnostic.txt, and A-SCALA.txt. The two files are for MFCL testing, and contain tag release-recapture data by fishery and period, along with information on the structure of the analysis, nominal effort, catch (pieces for longline fleets, metric tons for others), and catch length frequencies by stratum. The third holds summary data similar to one of the MFCL output files (plot.rep). Both summary files can be examined visually with MULTIFAN-CL Viewer to contrast the actual and estimated values. The fourth file is used to examine some of the key outputs of the simulator mainly for verification purposes. The last file consists of catch, effort and length frequency records in a format suitable for analysis with the A-SCALA model.

To comply with MCFL data input formats, the simulator converts data during the simulation. MFCL processes all data in 3 months time steps, so catch, effort and catch length frequencies are pooled by quarter. Similarly, fish ages (max. 84 months) are stratified into 10 quarterly age groups, with the oldest (plus group) containing all fish > 60 months of age. The number of recruits per quarter is set to the number of yellowfin of monthly ages 2, 3 and 4 (quarter 1) alive at the beginning of each quarter. Natural mortality rates are obtained from the weighted average of all monthly age groups comprising each quarterly age group.

Exploratory testing

The first series of tests (>70) were aimed at finding potential logic or programming errors in the simulator code that would cause unreliable outputs. The details of such tests are too extensive for this report, so only a brief summary follows. By and large, the simulated catch trends, catch length frequency distributions and tag recovery patterns matched the observed trends. Some data sets were subject to preliminary MFCL analysis, and most of the parameters estimates were comparable the values used to generate the data. In some cases, substantial discrepancies were detected, and resulted from the simulator's inability to reproduce certain features of the fishery, or produce outputs were not comparable with those of MFCL. These problems were corrected by adding new functions to the simulator, reformatting some outputs, adjusting some functions, or modifying the MFCL set-up procedures to search the entire parameter space of the test conditions.

Subsequent tests indicated that the MFCL estimates of biomass, mortality, growth, gear selectivity, recruitment, fishery impacts were close to the actual values, under simple simulation conditions (no differential growth, no measurement/observation errors, recruitment series with modest stochastic noise, etc.). Under more complex conditions, the reliability of some estimates decreased to a greater or lesser extent. Efforts were made to identify the types of adjustments necessary to improve the accuracy of the estimates under such conditions, and in some cases, changes made to the MFCL code lead to substantial improvements in fit. The exploratory testing phase ended when no coding or logic errors could be detected in both models, and no further adjustments could be justified.

MFCL testing procedure

An assessment of the accuracy, precision and bias of MFCL estimates was conducted by means of Monte Carlo simulations, whereby multiple data sets are sequentially generated under specific fishery conditions, and then analysed with MFCL using a single set-up configuration. Each data set is generated with a unique combination of random number seeds that translates into unique time series of recruitment, fish distributions, tag recovery patterns and error terms. Any given combination of time series is considered as a possible realisation of the fishery.

All tests described below were done with versions 19 of the simulator, and version 1024 of MFCL. The later generates estimates on length-at-age, F-at-age, M-at-age, movement, tag recovery, tag reporting, catch, spawning biomass, total biomass, recruitment, catchability, effort deviations, selectivity patterns, spawner-recruit ratios, yield per recruit and MSY. The test comparisons conducted so far focused on only a subset of these, namely length-at-age, M-at-age, F-at-age, spawning and total biomass, recruitment, natural mortality, and fishing mortality. This was done partly due to time restrictions, and because these are the main factors used to estimate PRPs.

With regards to total biomass, two trends are generated by each model, namely biomasses in the absence and presence of exploitation (Fig. 6). The simulator generates the first trend by setting F=0 for all periods, and the second trend with exploitation enabled over all periods. MFCL estimates both trends simultaneously. One reference point commonly used by management agencies is the ratio of biomass in the final year to that in the first year (B_{end}/B_{start}), with the later biomass considered as being representative of the initial virgin or unexploited biomass. Given two distinct biomass trends, the biomass ratio can be computed in the conventional way, or alternatively, from the biomass in the final year with exploitation OFF and ON. The later ratio might turn out to be a more suitable PRP because the initial biomass is not necessarily more representative of the virgin biomass, and (*i*) recent changes in environmental conditions that affect the productive capacity of a population are taken into account. In any case, both ratios are computed here for comparative purposes. The labels used to denote the statistics used are as follows

B_s, B_e = Biomass at the start, and at the end of the series, fishing OFF

BF_s, BF_e = Biomass at the start, and at the end of the series, fishing ON

B_e/B_s = Biomass ratio, fishing OFF

BF_e/BF_s = Biomass ratio, fishing ON

BF_e/B_e = Biomass rati o, fishing ON/OFF

All estimated trends (length-at-age, M-at-age, F-at-age, recruitment, spawning and total biomass) are compared to the simulated trends. To facilitate the visualisation of precision and accuracy, proportions (Estimated/Simulated) are computed for each point in the series. For cases with several realisations, the highest, lowest and mean proportions are computed for all values in the series. Additional statistics are also computed to comply with the SCTB 14 Methods Working Group requirements for multi-model testing. These consist of (i) the average spawning biomass over the first and last 3 quarters, (ii) average recruitment over the simulation period, and (iii) average fishing mortality over the last 3 quarters, obtained from the total catch over total abundance (in numbers) for of all age groups.

Description of MFCL test scenarios

The test scenarios range from overly simplistic, to fairly complex ones that mimic actual conditions in the YFT fisheries of the WCPO. Unless stated otherwise, data structures and parameter values of the simulator are as described previously. However, for each scenario, specific changes were made to modify the context.

Scenario 1: Single longline fishery, region, and realisation. M-at-age decreases linearly from 0.43-0.24 per quarter for quarterly ages 1-7, then increases linearly up to 0.47 for quarterly age 13-20. Von Bertalanffy growth, with identical patterns for males and females. Standard deviation in length-at-age is a linear function of the mean (SD = 1+ .05mean). The proportions at maturity are 0% for 1-7, 50% for ages 7-8, and 100% for older ages. Stochastic recruitment (CV ˜ 1.0). Size at recruitment is 36 cm after 2.5 months of growth. Selectivity increases from 0.05 to 1.0 over ages 1-9. Catchability increases by 1.6%/yr. Catch length frequency samples represent 0.5% of actual frequencies. Tag reporting is 100%. No SOI effects on movement.

Scenario 2: Single longline fishery and region. Ten realisations. M-at-age as for scenario 1. Von Bertalanffy growth, with identical patterns for males and females. Standard deviation in length-at-age is a linear function of the mean (SD = 0.1 mean). Maturation rates as in scenario 1. Recruitment as in scenario 1, centred on a level 30% higher. Size at recruitment is 31 cm after 2 months of growth. Catchability as in scenario 1. Selectivity increases from 0.35 to 1.0 over ages 1-7. Catch length frequency samples represent 2% of actual frequencies. Tag reporting is 100%. No SOI effects on movement.

Scenario 3. Two longline fisheries and regions (WCPO, east and west of 180°). Ten realisations. Selectivity for fishery_1 increases from 0.4 to 1.0 over ages 1-14, and 0.25-1.0 for fishery_2. Catchabiltity of fishery_1 is 50% higher than fishery_2. Catchability and selectivity patterns remain fixed through time. Growth patterns, maturation rates, recruitment patterns, size at recr uitment, catch sampling rates, and tag reporting as for Scenario 2.

Scenario 4. 16 fisheries and 7 regions scenario, representing the YFT fishery in the WCPO as described earlier. Ten realisations. Yellowfin growth pattern, with sex-specific growth rates. Fishery-specific selectivity patterns for non-longline fisheries. Fishery-specific catchability rates, with seasonal changes in longline catchability. No additional variation in selectivity and catchability. Time series of effort for all fisheries/periods contaminated with random log-normal error (CV = 0.2). Catch length frequency samples as in OFP records. Maturation rates and recruitment patterns as described for scenarios 2-3. Fishery-specific tag reporting rates for all but 3 pairs. No SOI effect on fish movement.

Test Results

Scenario 1: MFCL could not detect the first age class, partly because the simulated SD to mean relation in length-at-age did not comply fully with the MFCL hypothesis. This is shown by positive deviations in fork length for quarterly ages 1-2 (Fig. 7). M-at-age estimates are 0-50% lower than actual values for the youngest and oldest ages. Total and spawning biomass estimates are 2-3 times higher than actual values, and fishing mortality is about half of the actual values. On average, estimated recruitments are close to actual values, but at times, were up to 3 times higher than actual. F-at-age estimates were about half of the actual figures, as with the overall fishing mortality trends. All biomass ratios were within 3-14% of the actual values (Table 2).

Scenario 2: Estimated lengths-at-age are very close to actual values (Fig. 8). M-at-age deviations were as for scenario 1. Total and spawning biomass estimates are about double the actual values. Overall fishing mortality estimates are 30% less than actual ones, and average recruitment was 60% greater than actual recruitment. Trends in estimated F-at-age were similar to trends in total fishing mortality even for the single realisation. All biomass ratios were within 1-15% of the actual values (Table 2).

Scenario 3: Estimated lengths-at-age are nearly identical to actual values (Fig. 9). M-at-age show substantial departures from actual values for ages 1-2 and 6-7. On average, total and spawning biomass estimates were about 30% higher than actual values. Overall fishing mortality trends vary about the actual values, and average recruitment is about 30% higher than actual trends. Trends in estimated F-at-age were similar to trends in total fishing mortality even for the single realisation. Two of the biomass ratios were almost twice the actual values, but Bfe/Be was 8% less than the actual value (Table 2).

Scenario 4: Estimated lengths-at-age are nearly identical to actual values, even with sex-specific differences in growth rates, and a growth rate reduction at maturity (Fig. 10). M-at-age show large departures from actual values for middle-ages. On average, total and spawning biomass estimates were very close to actual values. Estimates of fishing mortality were not computed in an identical fashion for both models, so no deviations are shown, but the comparable values were similar across all periods. Average recruitment is about 50% higher than actual trends. Estimates of F-at-age were close to actual values for most periods. All biomass ratios were within 3-10% of the actual values (Table 2).

Discussion

In all cases tested, there were deviations from the actual values. The nature of the factor(s) responsible for the deviations cannot always be established with certainty. Discrepancies can result from coding errors, insufficient data of certain type (like tagging), time series lacking contrast, MFCL configuration errors (flags not turn on, wrong priors), parameter confounding problems requiring some re-parameterisation, limits of function minimisation routines, and etc. Additional testing and development will be required to ensure that all deviations caused by modelling practices are minimised, so that the residual deviations are largely context specific. In the absence of evidence to the contrary, and for the purposes of the following discussion, it is hypothesised that the deviations observed are mainly due to the complexity of the scenarios and data limitations.

By and large, the test results show that MFCL tends to provide more accurate estimates for complex scenarios than for overly simplistic scenarios. Presumably, the former yields more informative data than the later (like 1Fx1R). Although none of the estimated trends perfectly matched the actual ones, the deviations are considered to be relatively small, and less than or equal to what has been observed in similar tests (see NRC 1998, appendix 1). All biomass ratios in the most complex case (akin to YFT fishery in WCPO) were within 10% of the actual values. These biomass ratios are considered as key reference points, so MFCL estimates of these points are not seriously biased, even if the estimated biomass trends used to compute them differ from the actual trends to a greater extent. Of all biomass ratios tested, MFCL provided estimates of Bfe/Be that were the most consistently closer to the actual values.

Obviously, further testing is required to assess the reliability of MFCL estimates under more representative conditions of the yellowfin fishery in the WCPO. During the next 12 months, additional scenarios used will involve progressive increases in catchability, changes in selectivity, use of weight frequency data, allow for SOI effects on fish distribution, and make recruitment dependent on spawning biomass. Adding a stock-recruitment function to the simulator will provide more biological realism, and allow MSY-based reference points to be generated (B_{msy}, F_{msy}). This in turn will make it possible to evaluate MFCL estimates of MSY-based reference points such as (B_e/B_{msy}, F_e/F_{msy}), and proxy-based reference points (F_{msy} = 0.8 $M_{average}$, and B_{msy} = 0.4 B_o). Current plans are to generate two additional PRPs that are commonly used, namely F_{max} and $F_{0.1}$. These will be obtained from a yield-per-recruit analysis, done with the simulator by repeating the scenario several times as effort multipliers are applied. Once the simulated values are available, tests will be conducted to determine the reliability of the corresponding MFCL estimates. The results of the tests should help identify which of the PRPs MFCL can estimate most accurately. This will be considered when decisions are made as to which PRP should be used eventually, and whether or not the estimates should be corrected for apparent bias.

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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**	**Information source**
Growth patterns		X		SPC records
Length-at-age		X		SPC records
Weight-at-length		X		SPC records
Length-at-weight		X		SPC records
Maturation rates			X	Literature survey
Egg production		X		Literature survey
Recruitment pattern			X	MFCL analysis
Natural mortality		X		MFCL analysis
Environmental effects			X	SPC investigations
School movement			X	Tracking studies, ++
Adult distribution	X			Literature survey
Catchability rates		X		Model calibration
Gear selectivity		X		MFCL analysis
Effort distribution	X			Various reports
Catch composition	X			Various reports
Tag release-recapture	X			SPC investigations
Tag reporting rates		X		SPC investigations
Observation errors			X	Literature survey
Error structures			X	Various studies

Table 2. Summary results for the 4 test scenarios. The heading labelled 1Fx1R - 1 indicates a 1 fishery by 1 region context, single realisation. MFCL/OM indicates the value estimated by MFCL divided by the corresponding value generated by the simulator. For all cases with 10 realisations, the values represent averages over all realisations.

Scenario & realisation(s)	MWG-1 OM_actual	1Fx1R - 1 MFCL/OM	MWG-2 OM_actual	1Fx1R - 10 MFCL/OM
FL-at-age (range)	36 - 140	1.03	32 - 140	1.00
M-at-age (range)	0.48 - 0.24	0.84	0.47 - 0.24	0.83
Mean biomass (mt, F=ON)	2.07E+06	2.46	2.32E+06	1.82
Mean biomass start	2.71E+06	2.16	2.98E+06	1.64
Mean biomass end	1.98E+06	2.46	2.57E+06	1.68
Mean S_biomass (mt)	8.53E+05	2.47	9.01E+05	2.05
Mean S_biomass start	1.34E+06	1.80	1.36E+06	1.52
Mean S_biomass end	1.12E+06	2.23	9.26E+05	1.94
Mean recruitment	6.96E+07	1.19	8.80E+07	1.61
Overall F by quarter	0.300	0.60	0.033	0.72
Mean F start	0.035	0.59	0.036	0.68
Mean F end	0.022	0.55	0.021	0.80
Be/Bs	0.891	1.03	1.021	1.01
Bfe/BFs	0.732	1.14	0.870	1.04
Bfe/Be	0.771	1.14	0.796	1.05
Scenario & realisation(s)	MWG-3 OM_actual	2Fx2R - 10 MFCL/OM	MWG-4 OM_actual	16Fx7R - 10 MFCL/OM
FL-at-age	31 - 140	1.01	31 - 144	1.02
M-at-age (range/Q)	0.53 - 0.13	0.89	0.53 - 0.13	1.35
Mean biomass (mt, F=ON)	4.31E+06	1.32	6.18E+06	1.05
Mean biomass start	8.16E+06	0.67	7.74E+06	1.20
Mean biomass end	4.88E+06	1.18	5.19E+06	1.60
Mean S_biomass (mt)	2.38E+06	1.33	4.64E+06	0.88
Mean S_biomass start	5.79E+06	0.49	5.98E+06	0.81
Mean S_biomass end	2.94E+06	1.19	3.78E+06	0.89
Mean recruitment	9.70E+07	1.37	9.45E+07	1.57
Overall F by quarter	0.07	0.90	0.0268	n/a
Mean F start	0.10	0.99	0.0036	n/a
Mean F end	0.05	0.98	0.0468	n/a
Be/Bs	1.067	1.94	1.005	1.08
Bfe/BFs	0.598	1.80	0.670	1.10
Bfe/Be	0.486	0.92	0.660	1.03

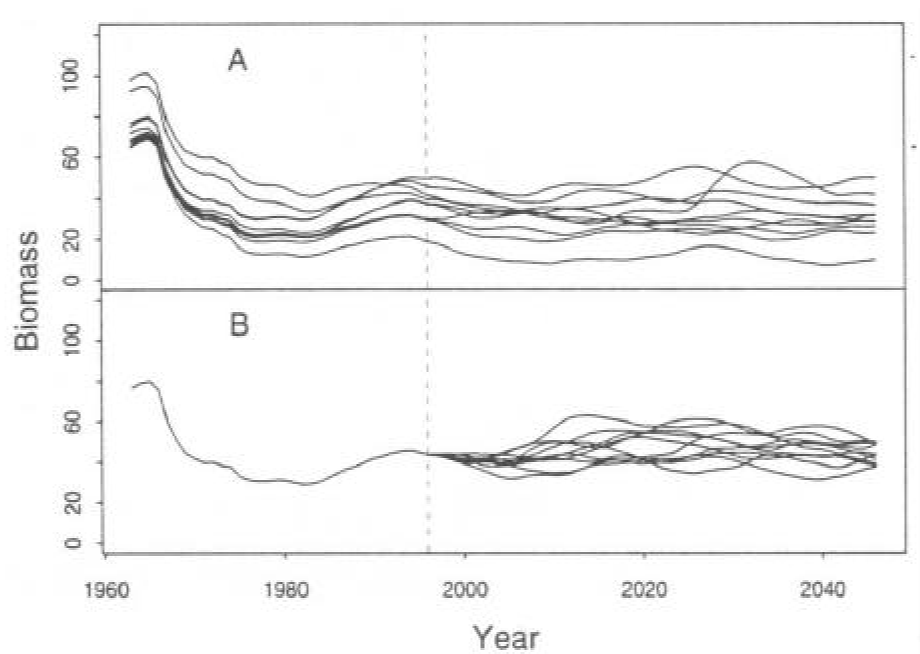

Figure 1. Ten sample trajectories of stock biomass from model reconstruction and forward projections under a catch policy of 2,000 t for the full model error approach (top), and future recruitment error approach (bottom). The vertical dashed line identifies the final year of reconstruction. (From Richards et al., 1998).

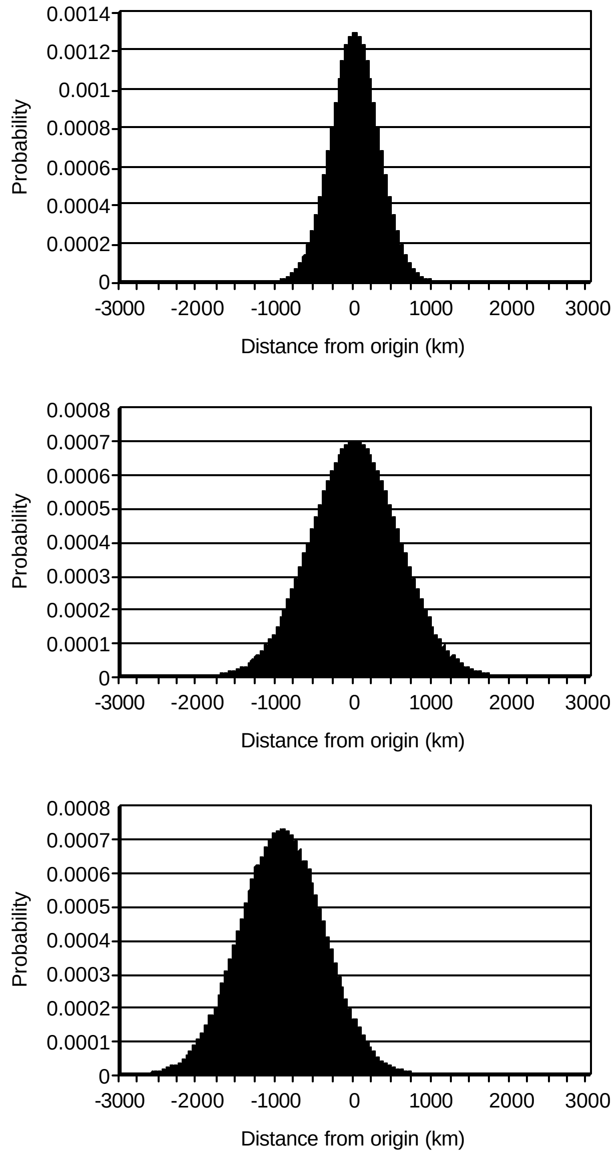

Figure 2. Monthly displacement probabilities. Top and middle distributions computed with unbiased random walk model for 70 and 130 cm yellowfin respectively. Lower distribution based on biased random walk model (p = 0.35) for 130 cm fish. Negative distances represent westward or southward displacements.

Lon	E	E	E	E	E	E	E	E	E	E	E	E	E	E	W	W	W	W	W	W
Min_d	110	115	120	125	130	135	140	145	150	155	160	165	170	175	180	175	170	165	160	155
Max_d	115	120	125	130	135	140	145	150	155	160	165	170	175	180	175	170	165	160	155	150
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
35_40						JP														
30_35																				
25_30		CH																		
20_25				62	65		38	68												
15_20				50		5														
10_15				20	17				77						77	83				
5_10				23	59	53														
0_5	ML			47	32	56								71						
5_0				35										65						
10_5							PNG						74	62		50				
15_10																53	38	26	17	
20_15																		29	5	14
25_20					AU												35	32		41
30_25																				
35_30																				
40_35														NZ						

Figure 3. Displacements of two schools during their period of existence. The schools recruited in the eastern and western sections of the WCPO. The numbers indicate the age (in months) of the school members at the time when they occupied the region. Locations were determined at 3 month time intervals, so intermediate positions not shown for purposes of clarity.

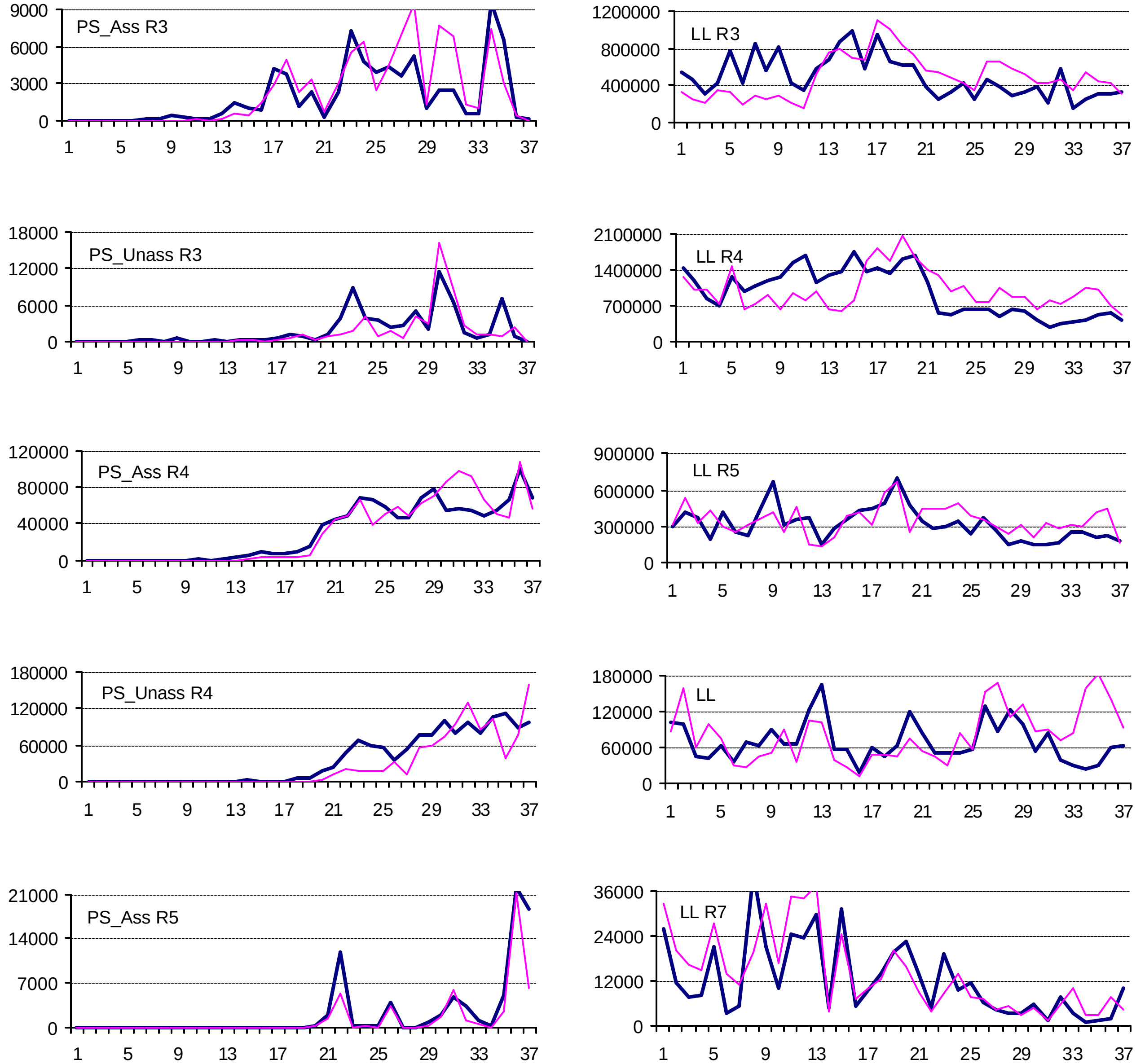

Figure 4. Actual versus simulated trends in annual catches for selected WCPO fisheries. Simulated trend (thick line) based on actual effort series, with no observation or measurement errors specified.

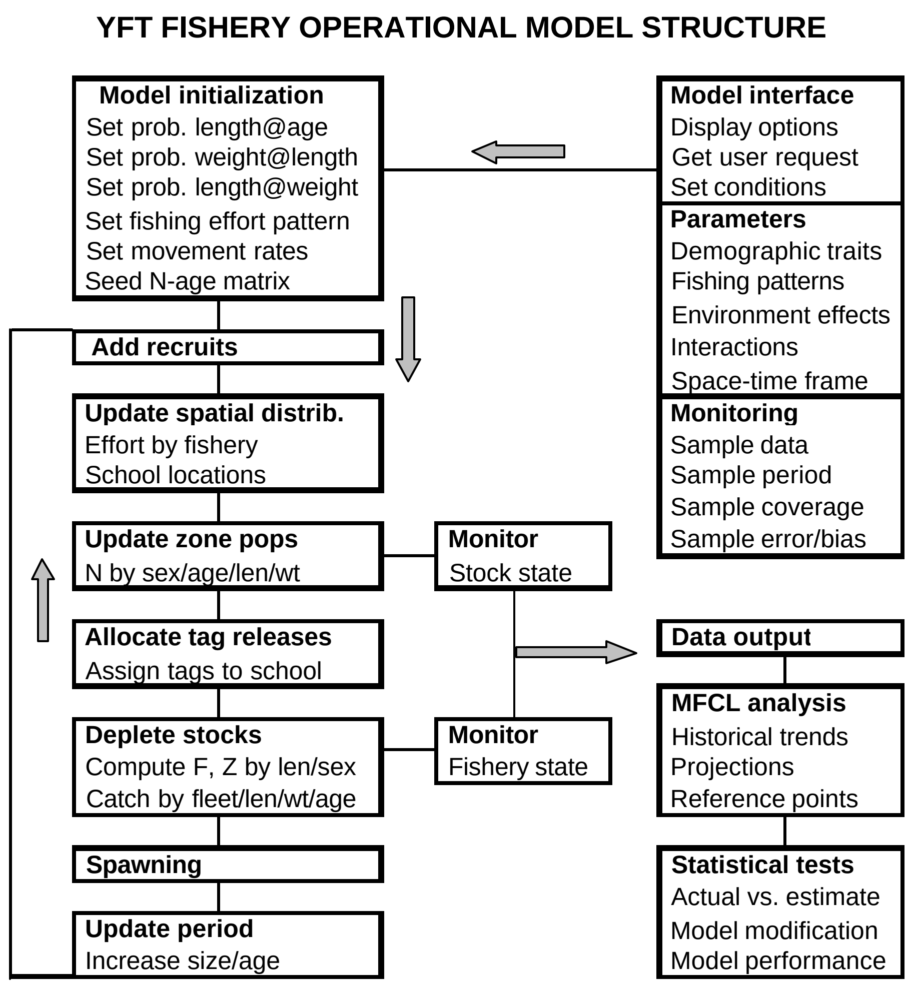

Figure 5. Structure of simulator as used for evaluating the performance of MULTIFAN -CL under various conditions.

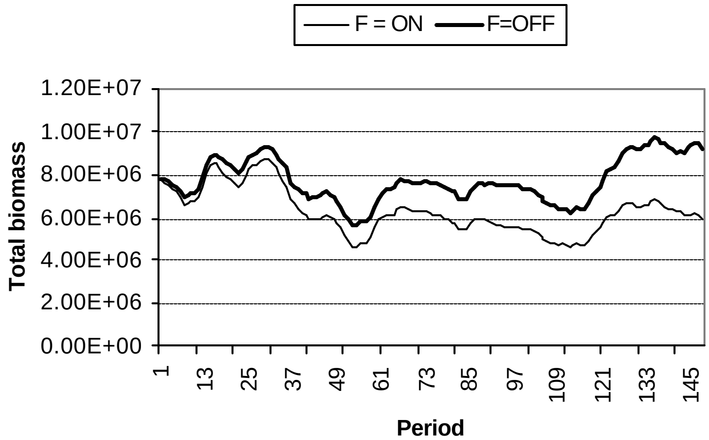

Figure 6. Trends in total biomass, estimated with exploitation enabled (F=ON), and without exploitation (F=OFF).

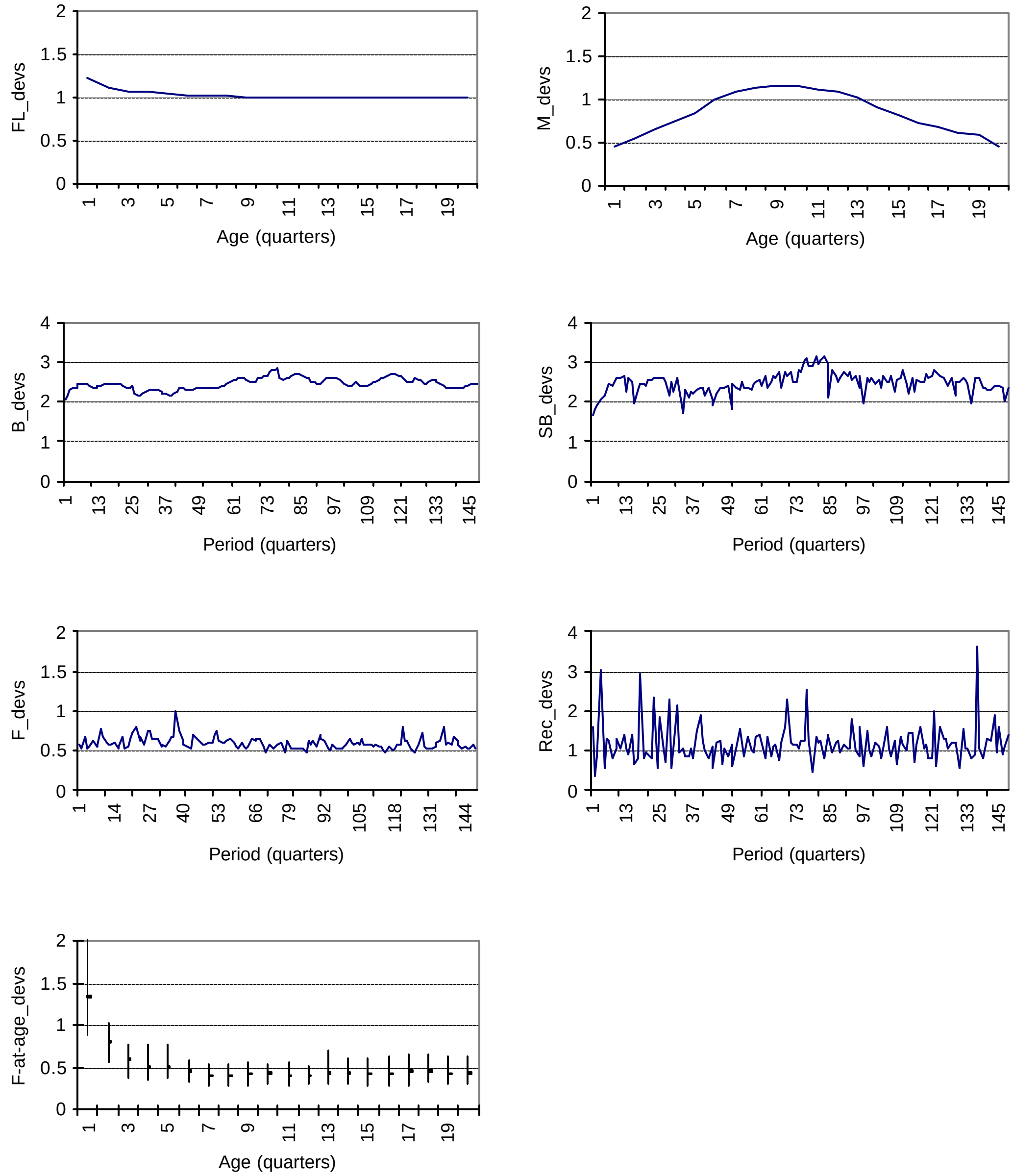

Figure 7. Summary statistics for scenario 1. Deviations expressed as estimated/simulated values. Ordinate labels indicate fork length (FL), natural mortality (M), total biomass in presence of fishing (B), spawning biomass (SB), overall fishing mortality (F), recruitment (R), and fishing mortality by age, across periods, single realisation, for ages subject to significant mortality (F-at-age/quarter > 0.01).

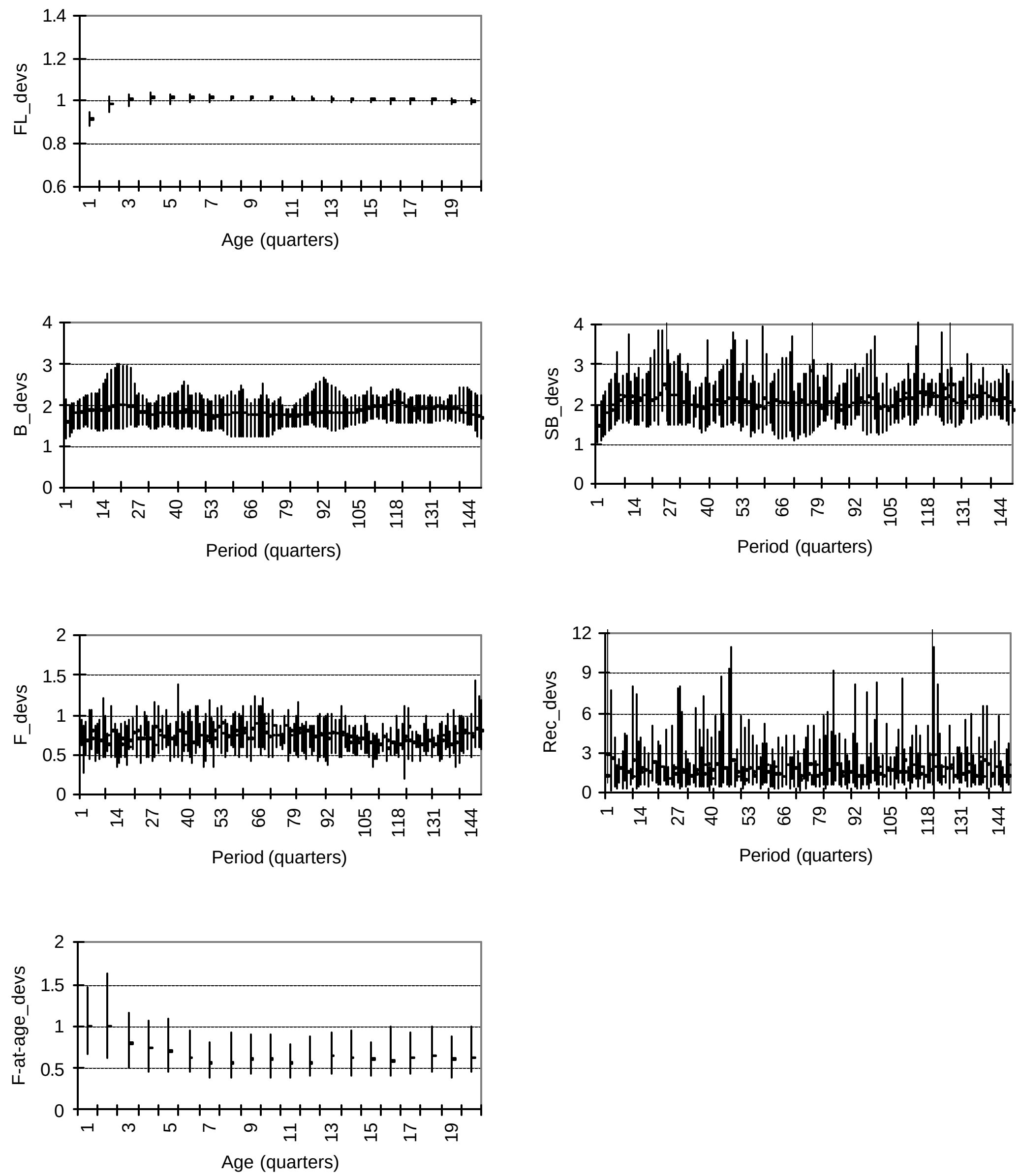

Figure 8. Summary statistics for scenario 2. Deviations expressed as estimated/simulated values. Vertical bars indicate the highest, lowest and mean deviation for 10 realisations, except F-at-age. Ordinate labels indicate fork length (FL), natural mortality (M), total biomass in presence of fishing (B), spawning biomass (SB), overall fishing mortality (F), recruitment (R), and fishing mortality by age, across periods, single realisation, for ages subject to significant mortality (F-at-age/quarter > 0.01).

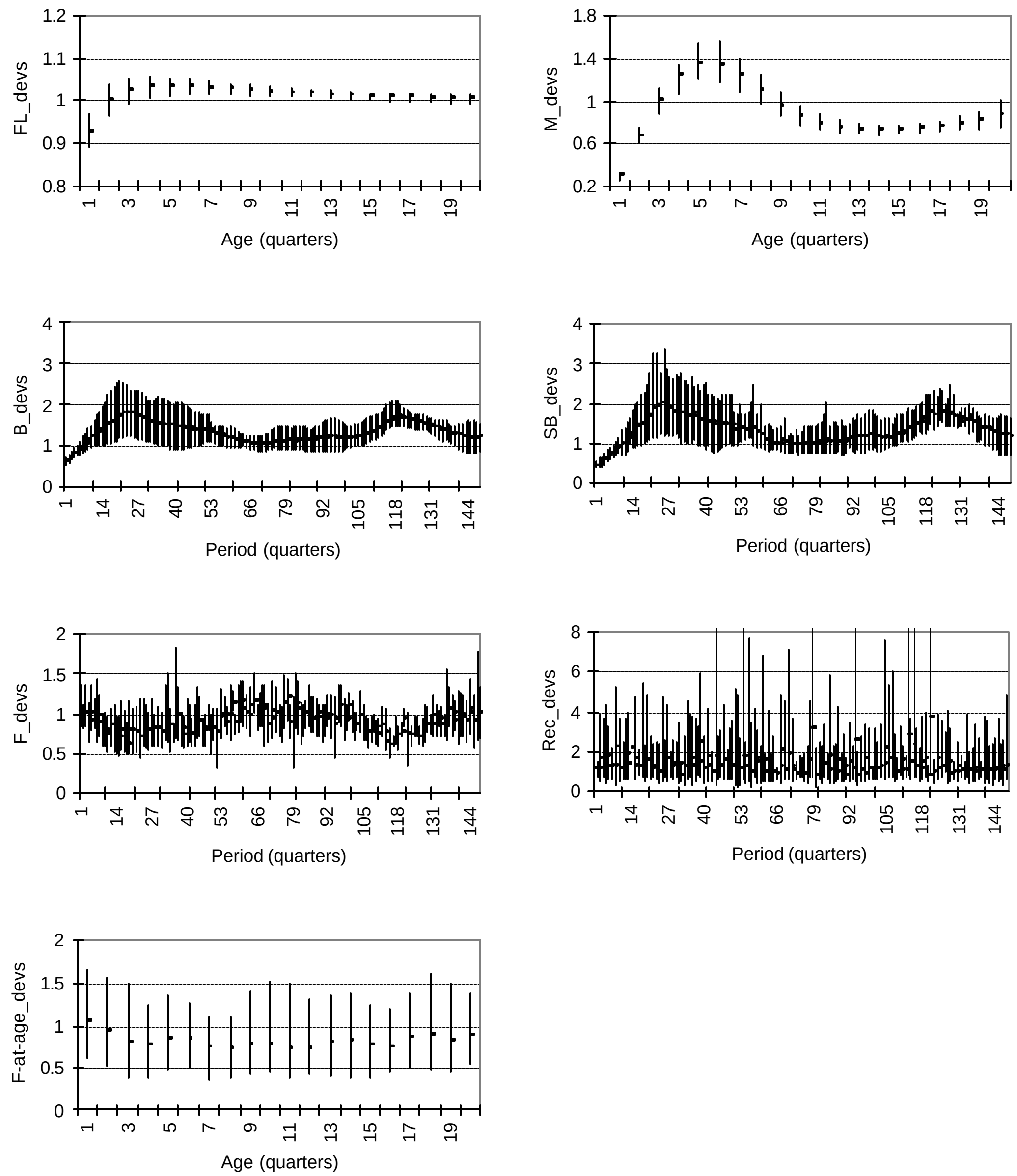

Figure 9. Summary statistics for scenario 3. Deviations expressed as estimated/simulated values. Vertical bars indicate the highest, lowest and mean deviation for 10 realisations, except F-at-age. Ordinate labels indicate fork length (FL), natural mortality (M), total biomass in presence of fishing (B), spawning biomass (SB), overall fishing mortality (F) and recruitment (R), and fishing mortality by age, across periods, single realisation, for ages subject to significant mortality (F-at-age/quarter > 0.01).

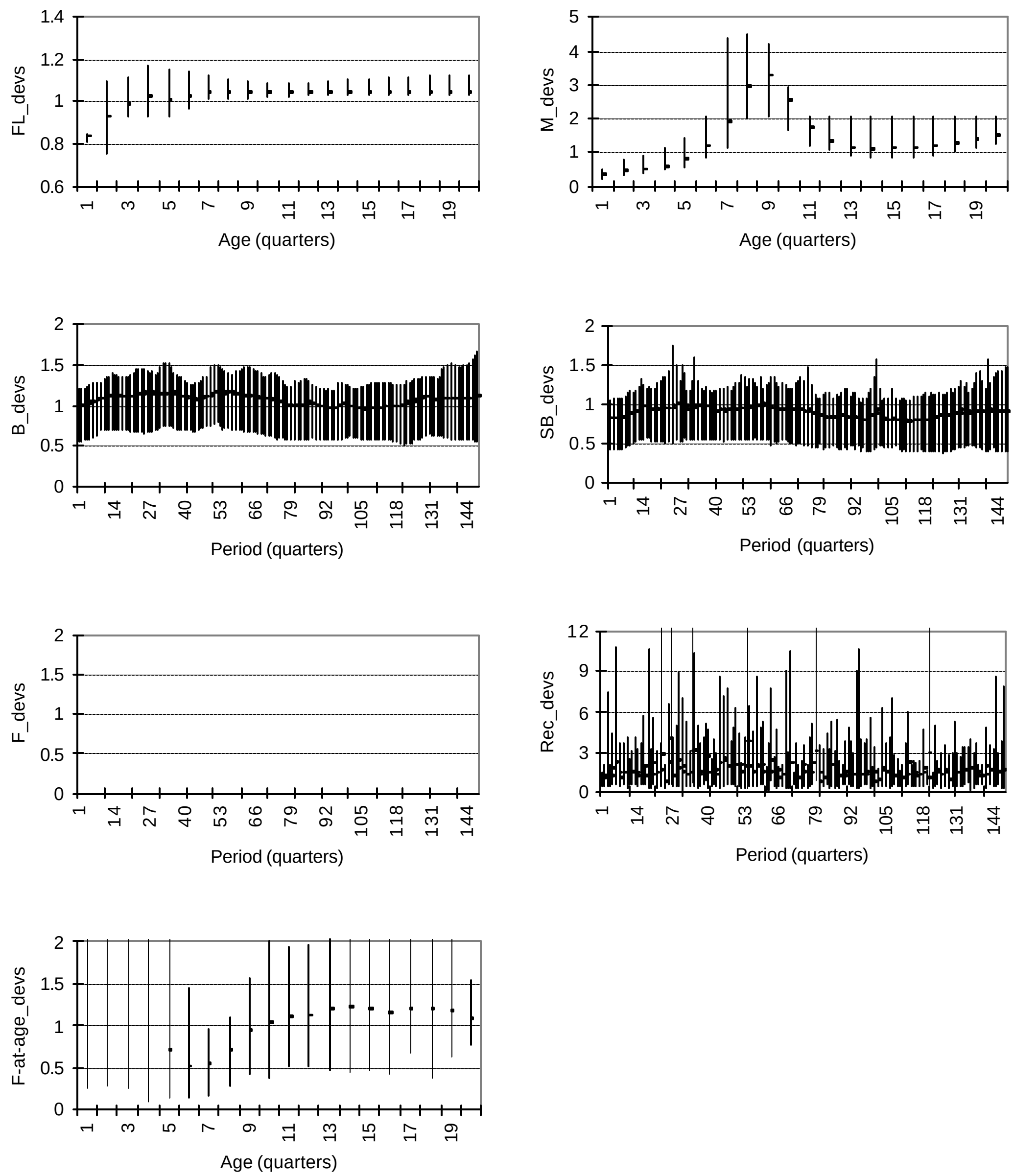

Figure 10. Summary statistics for scenario 4. Deviations expressed as estimated/simulated values. Vertical bars indicate the highest, lowest and mean deviation for 10 realisations, except F-at-age. Ordinate labels indicate fork length (FL), natural mortality (M), total biomass in presence of fishing (B), spawning biomass (SB), overall fishing mortality (F) and recruitment (R), and fishing mortality by age, across periods, single realisation, for ages subject to significant mortality (F-at-age/quarter > 0.01).