



MANAGEMENT STRATEGY EVALUATION FOR INDIAN OCEAN YELLOWFIN TUNA: DEVELOPMENT AND ANALYSIS OF OPERATING MODELS

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Purpose, expectation and action intended (select one or more and include corresponding text)

Discussions (for information and open discussion):

The paper informs meeting participants about the conditioning and validation of the operating model for Indian Ocean yellowfin tuna, based on the uncertainty grid defined from the yellowfin tuna stock assessment. It also presents a comparison between FLBEIA-compatible and SS3 reference point estimates and provides preliminary results from testing SPiCT as a stock-status estimator.

Feedback (to collect input and suggestions)

The paper requests review and comments on the operating-model conditioning choices, the estimation of FLBEIA-compatible reference points, and the preliminary use of SPiCT as a stock-status estimator.

Conclusion (to record a concluded position or summary)

The paper concludes that the 12-model operating-model grid and the SS3-FLBEIA consistency checks provide an appropriate basis for the next stage of management-procedure development.

Recommendation (to ask the meeting to endorse a recommendation)

The paper seeks support to continue the development of the Management Strategy Evaluation framework, including the incorporation of additional sources of uncertainty and the evaluation of candidate management procedures based on both model-based and empirical approaches.

Decisions (to request formal approval of actions)

No formal decision is requested at this stage.



Abstract

This paper describes the development and preliminary evaluation of operating models for the Management Strategy Evaluation (MSE) of Indian Ocean yellowfin tuna. A 12-model uncertainty grid was conditioned in FLBEIA based on the uncertainty structure adopted in the 2025 yellowfin tuna stock assessment, combining alternative assumptions regarding longline CPUE treatment, catchability creep, and stock-recruitment steepness. The analysis evaluates the consistency of the FLBEIA implementation with the original SS3 assessment, estimates FLBEIA-compatible biological reference points, and conducts deterministic projection diagnostics to verify model behaviour under alternative effort scenarios. In addition, SPiCT was tested as a potential stock-status estimator within a model-based management procedure. Results indicate that FLBEIA broadly reproduces the main historical dynamics and reference points obtained from SS3, while projection diagnostics showed coherent responses across the operating-model grid. SPiCT reproduced the principal trends in stock status, although it provided a more conservative relative biomass status estimate than the operating-model median. These results provide an initial basis for the development and testing of candidate management procedures for Indian Ocean yellowfin tuna.

Keywords: yellowfin tuna; Indian Ocean; management strategy evaluation; operating model; FLBEIA; Stock Synthesis; SPiCT; reference points.

Executive summary

- Twelve operating models were conditioned from the yellowfin tuna assessment, combining two longline-CPUE treatments, two assumptions about catchability creep and three stock–recruitment steepness values.
- The translation from SS3 to FLBEIA preserved the principal historical dynamics of spawning biomass, recruitment, catch and fishing mortality, despite differences in model spatial structure and fishery definition.
- FLBEIA generates catches from effort through a Cobb–Douglas relationship, whereas SS3 uses fishing mortality through the Baranov catch equation. Due to these differences and the ones mentioned previously, model-specific reference points were required.
- FLBEIA and SS3 reference points were broadly consistent. The largest reported discrepancy concerned SSB_{MSY} , with FLBEIA values up to 17% lower; MSY differences remained within 10%.
- The projection diagnostics behaved coherently under some sanity check scenarios: zero effort, continuation of terminal fishing mortality and F_{MSY} effort scenarios.
- SPiCT broadly reproduced the historical status trajectories, although its biomass ratio was lower than the OM median and its fishing-mortality ratio was higher. This combination provides a more conservative status signal than the median OM.
- The current operating-model grid provides a robust foundation for future MSE development and can be extended to include additional sources of uncertainty, such as recruitment deviations.

1. Introduction

Indian Ocean yellowfin tuna (*Thunnus albacares*) supports one of the most valuable tuna fisheries in the world and provides important economic, social, and food security benefits to coastal and distant-water fishing nations throughout the Indian Ocean. The stock is exploited by multiple fleets using different fishing gears across a broad spatial range, creating a complex management setting with diverse stakeholder interests and objectives.

The stock has been assessed regularly for more than two decades using a succession of increasingly sophisticated assessment methods. Early assessments were based on Virtual Population Analysis and production models (Nishida and Shono, 2005, 2007), followed by the implementation of MULTIFAN-CL (Langley et al., 2008, 2009, 2010, 2011, 2012) and, more recently, Stock Synthesis (SS3) (Langley, 2015; Methot and Wetzel, 2013). These assessments incorporated progressively richer sources of information, including tagging data, standardized CPUE indices, fishery-dependent biological data, and alternative hypotheses regarding population dynamics and fishery processes. Following the 2015 assessment, IOTC adopted an interim rebuilding plan for Indian Ocean yellowfin tuna under Resolution 16/01 (Res.16/01), which was subsequently revised through different resolutions which was subsequently revised through Resolutions 17/01, 18/01, 19/01 and 21/01..

Despite these advances, assessing Indian Ocean yellowfin tuna remains challenging. Recent assessments have highlighted the influence of alternative assumptions regarding stock structure, recruitment dynamics, CPUE standardization, growth, natural mortality, selectivity patterns, and tagging data on model outcomes. The development of model ensembles and extensive sensitivity analyses has improved the characterization of uncertainty, but differences among plausible model configurations continue to influence estimates of stock status and management reference points. These challenges are not unique to yellowfin tuna but reflect the inherent uncertainty associated with assessing highly migratory stocks exploited across large spatial scales by multiple fisheries.

Management Strategy Evaluation (MSE) provides a framework for addressing these uncertainties directly. Rather than relying solely on periodic stock assessments to guide management decisions, MSE evaluates the



performance of candidate management procedures across a wide range of plausible hypotheses regarding stock productivity, fishery dynamics, observation processes, and implementation uncertainty. This approach enables the identification of management procedures that are robust to uncertainty and capable of meeting agreed management objectives under a variety of future conditions.

The adoption of a tested management procedure would provide a more transparent, predictable, and robust basis for setting future Total Allowable Catches (TACs) for Indian Ocean yellowfin tuna. By evaluating candidate procedures before implementation, MSE allows stakeholders and managers to understand the expected trade-offs between stock conservation, rebuilding objectives, catch stability, and long-term yield, thereby supporting a more structured and risk-based management process.

This report describes the development and conditioning of operating models for Indian Ocean yellowfin tuna for use in Management Strategy Evaluation. The document outlines the operating model framework, the incorporation of uncertainty through a candidate model grid, and the procedures used to ensure consistency between the SS3 assessment framework and the FLBEIA implementation. It also presents the reference points adopted for the management strategy evaluation, the performance statistics used to evaluate candidate management procedures, and the basis for future testing of management procedures for the stock.

2. Methods

2.1 Operating-model grid and conditioning

The OM grid comprised 12 models based on three uncertainty axes. The longline CPUE series was either retained as a single series or divided before and after 2000 due to changes in selectivity. Longline catchability creep was either excluded or applied at 0.5% yr⁻¹. Stock–recruitment steepness (*h*) took values of 0.7, 0.8 or 0.9. The full factorial combination generated $2 \times 2 \times 3 = 12$ OMs.

Factor	Levels	Interpretation
Longline CPUE	NoSplit; SplitCPUE	Single series or division before/after 2000
Catchability creep	EC0; EC1	No creep or 0.5% yr ⁻¹
Steepness	0.7; 0.8; 0.9	Alternative stock–recruitment productivity assumptions

Table 1: The uncertainty axes defined in the OM.

Conditioning was based on the 2025 update of the Indian Ocean yellowfin tuna stock assessment, where the stock assessment models of 2024 were updated with the revised Joint longline CPUE indices. The models are based on SS3 models and transferred to FLBEIA using the *ss3om* R library. The biological component retained the age-structured representation and used a Beverton–Holt stock–recruitment relationship (Beverton and Holt, 1957) with parameters from SS3. Recruitment uncertainty was not included in the preliminary runs described in the source presentation.

2.2 Fleet structure

The FLBEIA operating model was configured as a one-area model with seasonal dynamics. The SS3 fleets were aggregated into eight gear-based FLBEIA fleets: gillnet (GI), handline (HD), longline (LL), other fisheries (OT), baitboat (BB), purse seine (PS), troll (TR), and FLL. Aggregation was based on similarities in fishery definitions and selectivity patterns in the SS3 assessment. Purse-seine fisheries were represented by a single FLBEIA fleet but separated into free-school (FS) and log-school (LS) métiers to preserve differences in selectivity and seasonal catch allocation. The SS3 fleet components included in each FLBEIA fleet are shown in the table 1:

OM fleet	Fleet	SS3 fleets and areas aggregated
GI	Gillnet	GI area 1a; GI area 4
HD	Handline	HD area 1a
LL	Longline	LL areas 1a, 1b, 2, 3 and 4
OT	Other fisheries	OT areas 1a and 4
BB	Baitboat	BB area 1b
PS	Purse seine, free-school	FS areas 1b, 2 and 4
PS	Purse seine, log-school	LS areas 1b, 2 and 4
TR	Troll	TR areas 1b, 2 and 4
FLL	Line fishery	LF area 4

Table 2: Aggregation of SS3 fisheries into FLBEIA operating-model fleets.

2.3 Catch production and fishing mortality

The principal structural distinction between implementations concerns catch production. FLBEIA is a multi-stock, multi-fleet, stochastic and seasonal simulation framework developed for the bio-economic evaluation of fisheries management strategies under an MSE approach (Garcia et al., 2017). In the current implementation, FLBEIA generates catch in numbers from fishing effort through a Cobb–Douglas production relationship (Cobb and Douglas, 1928; Garcia et al., 2017):

$$C = q E^{\alpha} N^{\beta}$$

where C is catch in numbers, q is catchability, E is fishing effort, N is stock abundance, and α and β are effort and abundance elasticities. The preliminary implementation fixed $\alpha = 1$ and $\beta = 1$ because no information was available to estimate them.

SS3 generates catches from fishing mortality using the Baranov catch equation (Baranov, 1918; Methot and Wetzel, 2013):

$$C = (F/Z) N_0 (1 - \exp(-Zt))$$

where F is fishing mortality, Z is total mortality, N_0 is abundance at the start of the time step and t is the duration of the time step. Both formulations were applied by fleet and season, while SS3 additionally contains explicit spatial structure.

2.4 Model verification

Historical time series were compared to identify translation errors and quantify structural differences. The checks covered numbers at age, body weight, maturity, landings at age and recruitment. Aggregate trajectories of spawning-stock biomass, catch, recruitment and fishing mortality were then compared across the OM grid.

Fishing mortality was treated cautiously because the reported quantities differ between platforms. In SS3, yellowfin fishing mortality is a weighted mean over ages 0.25–10.5. In FLBEIA, it is an instantaneous rate summarised by an arithmetic mean over ages 0–10. Comparisons were therefore examined under common age ranges, including ages 1–4 and ages 0–10, rather than assuming direct equivalence of the default metrics.

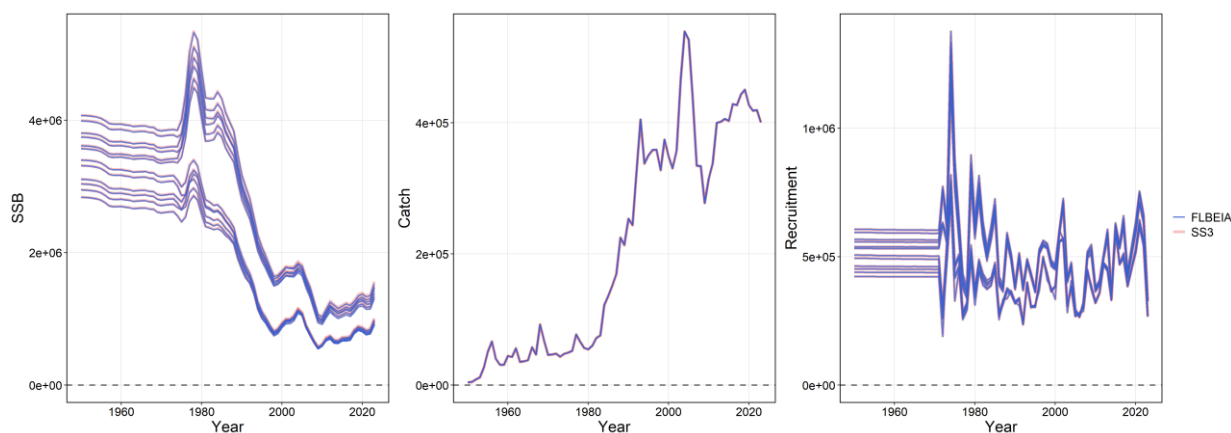


Figure 1. Historical comparison of spawning biomass, catch and recruitment in SS3 and FLBEIA.

2.5 FLBEIA-compatible reference points

Reference points were recalculated within FLBEIA to ensure compatibility with its effort-based catch process. Catchability was estimated by age and season from the average of the final three years:

$$q = \text{Catch} / [E \times N \times \exp(-m/2)]$$

where m is natural mortality. The final three-year average and its seasonal pattern were retained for projections, alongside the fleet and purse-seine métier shares described above.

The fleet shares assumed to estimate reference points are summarised in Table 2.

Fleet	Quota Share
LL	0.0396
PS	0.3124
BB	0.0287
TR	0.0428
FLL	0.1478
GI	0.1436
HD	0.2633
OT	0.0218

Table 3: Relative fleet shares based on the average landings composition of the last three years.

The seasonal purse-seine allocation to free-school and log-school métiers was derived from the average catch composition of the last three years. Free-school shares were 0.35, 0.35, 0.19 and 0.08 across seasons 1–4, respectively, with complementary shares assigned to log-school fishing.

2.6 Projection diagnostics

Three deterministic projection tests were used as basic sanity checks: zero fishing effort, continuation of effort associated with the terminal fishing mortality, and effort associated with F_{MSY} . Coherent responses were expected: rebuilding under zero effort, stabilisation according to terminal exploitation under the last-F scenario, and convergence towards target status under the F_{MSY} scenario.

2.7 SPiCT configuration

SPiCT is a continuous-time stochastic surplus-production model that represents both stock and fishery dynamics and accounts for process and observation error (Pedersen and Berg, 2017). SPiCT was tested here as a stock-status estimator for a model-based management procedure using catch and an unsplit abundance index. Priors were centred

on $K = 3,500,000$ t and $r = 0.2$ yr⁻¹, with log-scale standard deviations of 0.15 and 0.20, respectively. The production-function shape was fixed close to the Fox model ($n = 1$; $SD = 0.0001$). The initial biomass fraction was centred on 1 with $SD = 0.00995$, consistent with the SS3 assumption that the population was in an unexploited equilibrium state at the start of the assessment in 1950 (Urtizberea et al., 2024). The split-index configuration exhibited convergence problems under these assumptions.

Parameter	Mean	SD on log scale	Role
logK	3,500,000 t	0.15	Virgin biomass prior based on OM median
logr	0.2 yr ⁻¹	0.20	Intrinsic growth-rate prior
logn	1	0.0001	Fixed Fox-type production shape
logbkfrac	1	0.00995	Initial biomass fraction near unity

Table 4: Prior distributions used in SPiCT, including means and standard deviations on the log scale.

3. Results

3.1 Reference points

Reference points derived in FLBEIA were broadly consistent with those from SS3. Across the 12 OMs, relative differences in MSY remained within 10%. The largest discrepancy occurred for SSBMSY, for which FLBEIA estimates were up to 17% lower than the corresponding SS3 estimates. The direction of the SSBMSY difference was generally consistent across the grid, whereas MSY differences occurred in both directions.

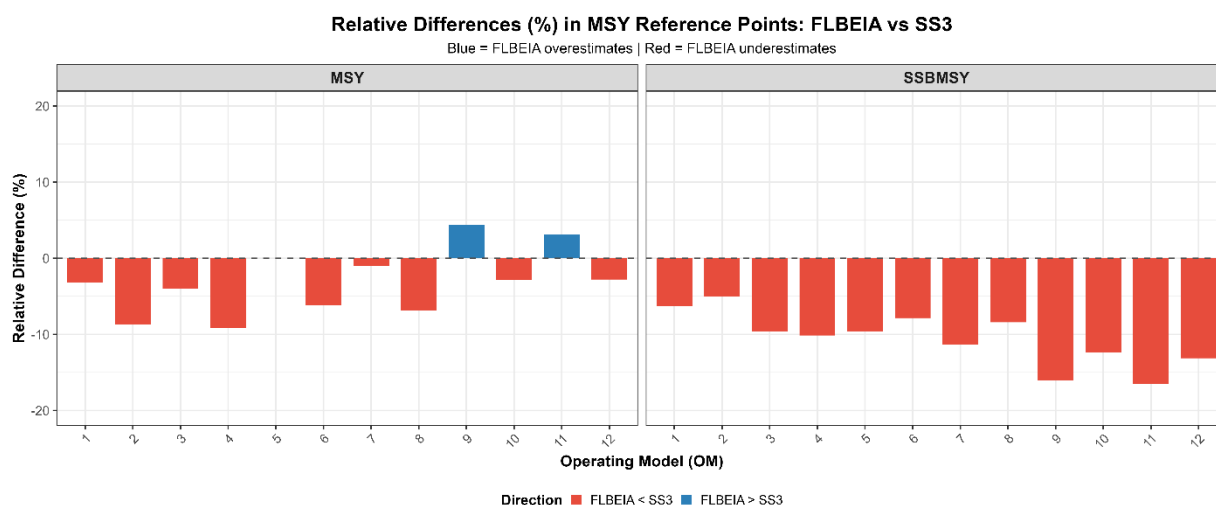


Figure 2. Relative differences in MSY and SSBMSY reference points between FLBEIA and SS3 across the 12 OMs.

3.2 Historical fit and sanity checks

The FLBEIA translations reproduced the principal historical patterns from SS3 in spawning biomass, catch and recruitment. The trajectories showed closely aligned timing and direction of change, including the decline in spawning biomass and the broad evolution of catches and recruitment. Remaining differences were associated with fleet aggregation, the conversion from spatial SS3 models to a one-area operating model, and the use of effort rather than fishing mortality as the immediate driver of catches.

Although the absolute spawning biomass trajectories were very similar between frameworks, larger differences were observed in the relative biomass indicator (SSB/SSBMSY). These differences were primarily driven by discrepancies in the estimated reference points rather than by differences in stock dynamics. Because FLBEIA generally estimated lower SSBMSY values than SS3, the resulting SSB/SSBMSY ratios were consistently higher in FLBEIA despite both frameworks producing similar estimates of absolute spawning biomass. Nevertheless, uncertainty intervals for the two frameworks broadly overlapped, particularly in the terminal years, indicating that the overall interpretation of stock status remained largely consistent despite differences in the scaling of the reference points.

Catch/MSY trajectories were closely aligned because the corresponding MSY estimates differed only marginally between frameworks. Similarly, the fishing mortality comparison showed only moderate differences, with part of the divergence in F/F_{MSY} arising from differences in the estimation and definition of fishing mortality and its associated reference points rather than from differences in the underlying exploitation history.

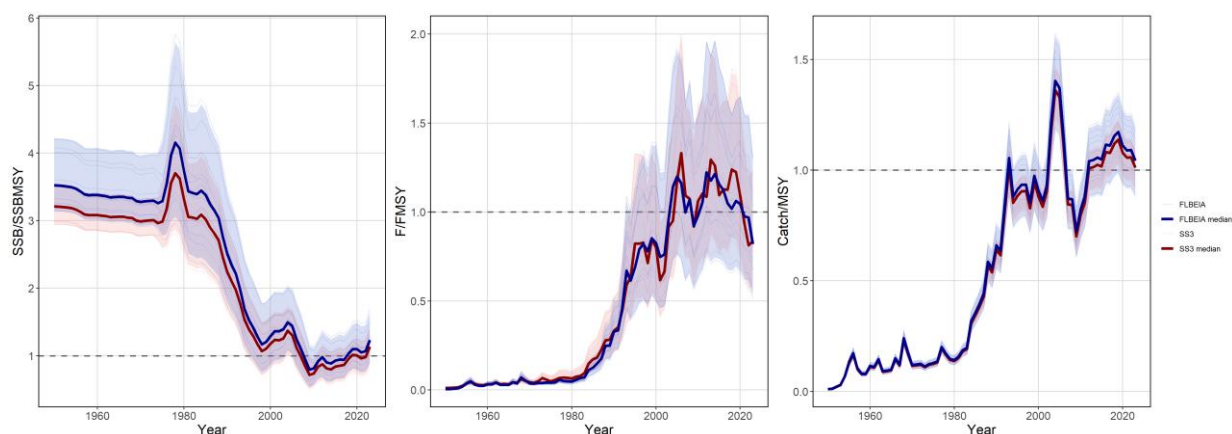


Figure 3. Comparison of relative biomass, fishing mortality and catch trajectories median across SS3 and FLBEIA; shaded areas are 95% confidence intervals.

3.3 Projection diagnostics

The zero-effort projection produced an immediate cessation of catches and fishing mortality, followed by rebuilding of spawning biomass. Under continuation of terminal fishing mortality, catches and biomass approached OM-specific levels consistent with persistent exploitation. Under effort associated with FMSY, status indicators moved towards the target region, although OM-specific differences remained because productivity and historical conditioning differed across the grid.

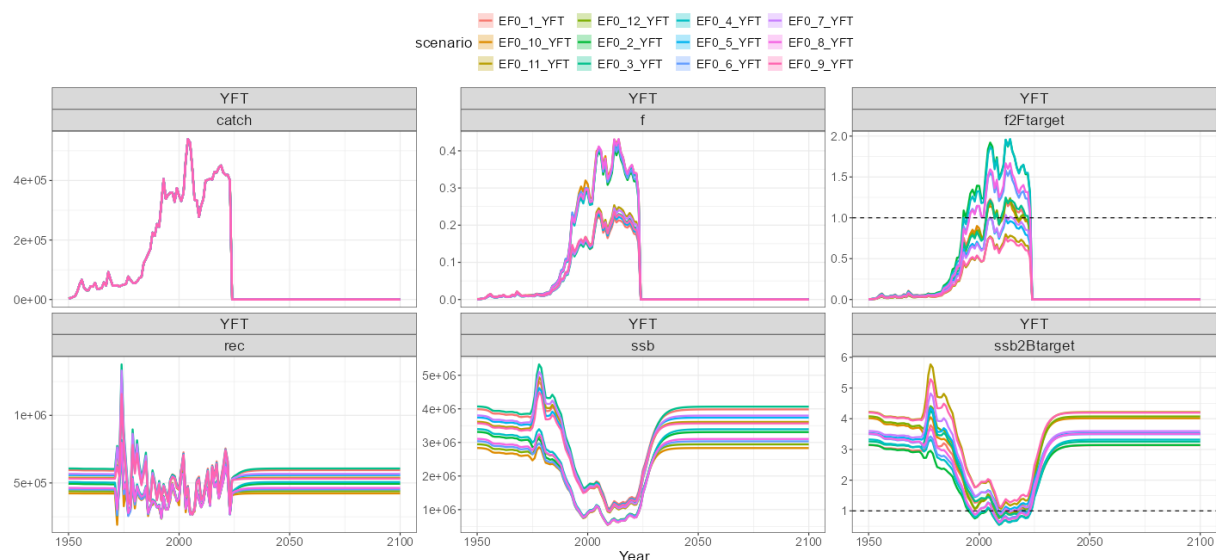


Figure 4. Zero-effort projection diagnostic across the operating-model grid.

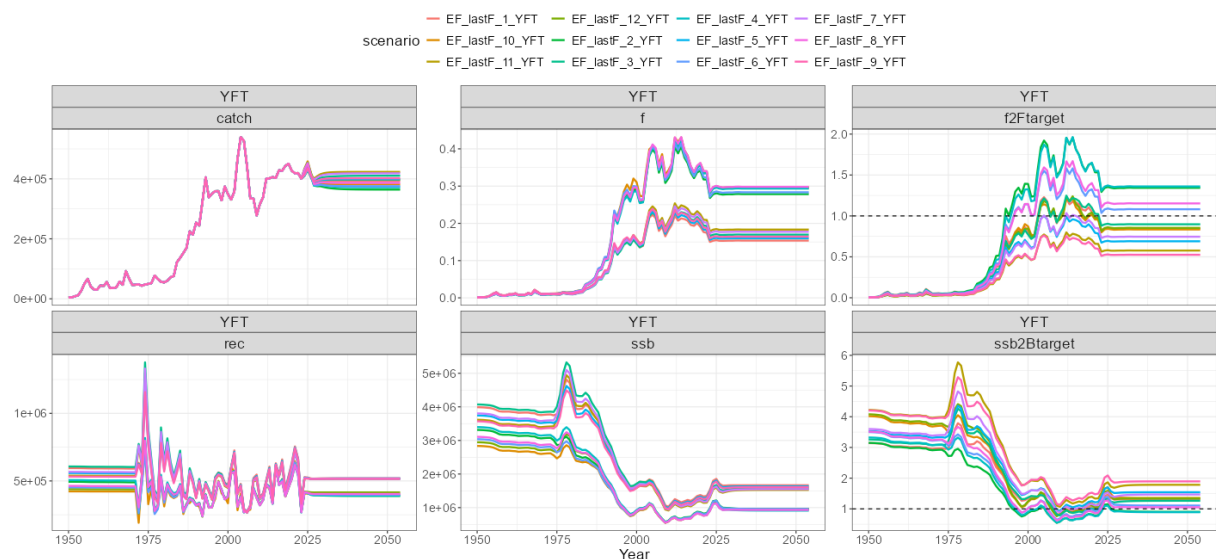


Figure 5. Projection diagnostic using the most recent effort.

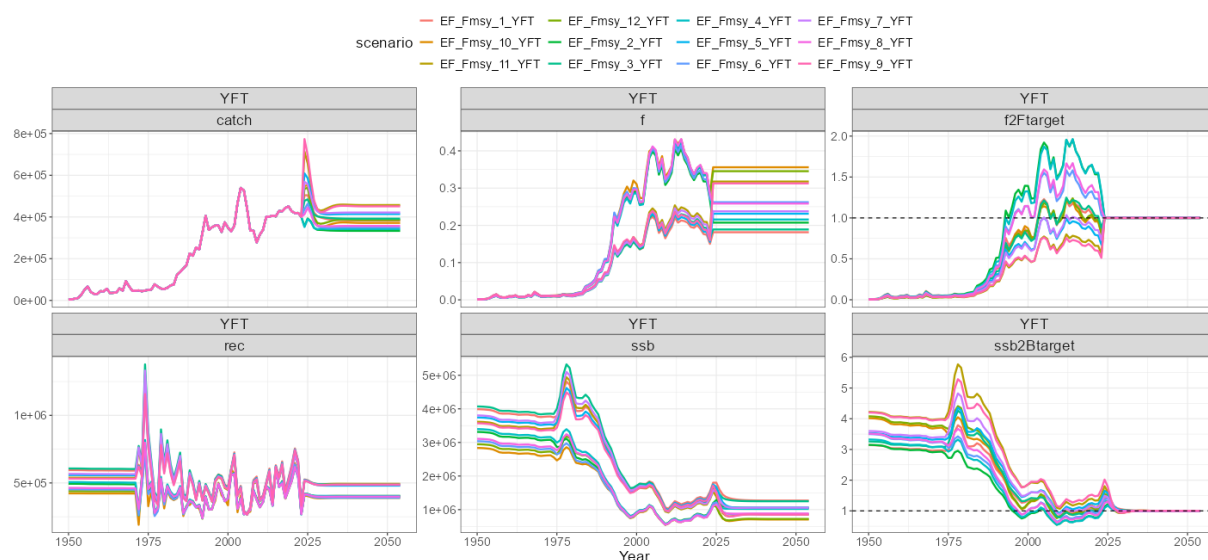


Figure 6. Projection diagnostic using effort corresponding to FLBEIA FMSY.

3.4 SPiCT performance

For the unsplit-index configuration, SPiCT converged and reproduced the broad historical trends in stock status. Terminal SPiCT estimates were $B/BMSY = 1.12$ and $F/FMSY = 0.96$. The corresponding OM distribution had a median $B/BMSY$ of 1.23 with a 95% interval of 0.90–1.65, and a median $F/FMSY$ of 0.82 with a 95% interval of 0.52–1.30 as reported in the source table. The SPiCT estimate therefore fell within the reported OM intervals for both relative-status indicators.

Variable	SPiCT	OM low 95%	OM median	OM high 95%
B/BMSY	1.12	0.90	1.23	1.65
F/FMSY	0.96	0.82	0.53	1.30
BMSY (t)	1,338,298	705,695	953,163	1,269,847
FMSY	0.28	0.18	0.25	0.36
MSY (t)	375,481	333,467.83	384,405	457,065

Table 4: Comparison between SPiCT estimates and the operating-model distribution for key management quantities.

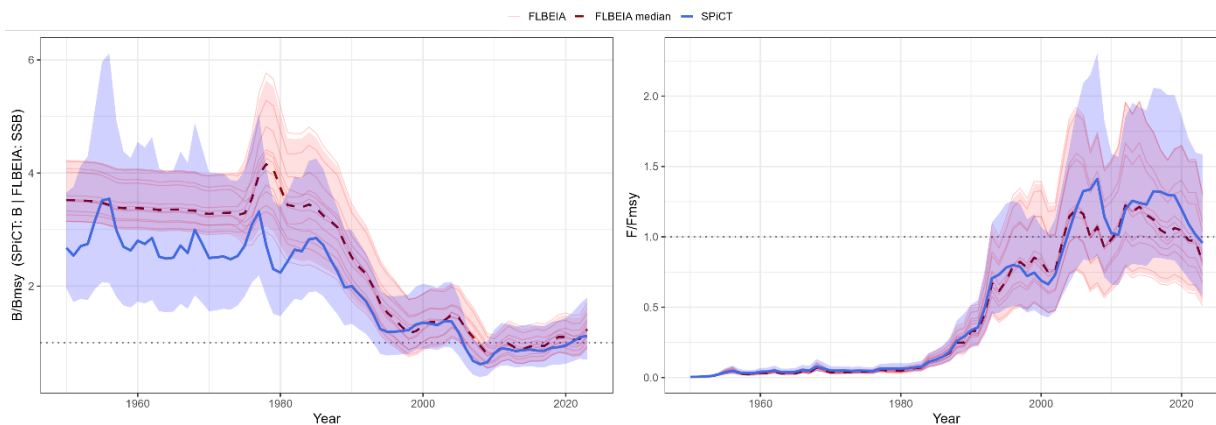


Figure 7. Historical comparison of relative biomass and fishing mortality estimated by SPiCT and the operating models.

Absolute reference points were also similar in scale. SPiCT estimated $F_{MSY} = 0.28$ and $MSY = 375,481$ t, compared with OM medians of 0.25 and 384,405 t. SPiCT B_{MSY} was 1,338,298 t, higher than the reported upper limit of the OM interval (1,269,847 t). This difference is consistent with the distinct biomass concepts: SPiCT estimates exploitable biomass in a production-model framework, whereas FLBEIA tracks spawning-stock biomass in an age-structured framework.

4. Discussion

4.1 Adequacy of the operating-model translation

The analysis of the conditioning indicates that the FLBEIA implementation retains the principal dynamics of the SS3 assessment while providing the effort-based and fleet-disaggregated structure needed for closed-loop MSE. Exact agreement between SS3 and FLBEIA is not expected because the two frameworks have different roles within the MSE process: SS3 is used for stock assessment, whereas FLBEIA is used for simulation and management strategy testing. SS3 is the assessment basis and contains four spatial regions, whereas the current FLBEIA OM is spatially aggregated. Similarly, fleet definitions were simplified for simulation, and catch production was reformulated from a fishing-mortality-based Baranov equation to an effort-based Cobb–Douglas relationship.

The historical overlays and projection diagnostics nevertheless show that these changes did not produce implausible dynamics. Agreement in median trajectories and uncertainty envelopes provides evidence that the OM grid captures the assessment's central stock history and a meaningful range of alternative productivity assumptions.

4.2 Interpretation of reference-point differences

The observed reference-point differences are modest for MSY but more systematic for SSB_{MSY} . A lower FLBEIA SSB_{MSY} can arise from differences in seasonal timing, fleet selectivity aggregation, spatial aggregation and the mechanics linking effort to catch. These factors affect equilibrium age structure and spawning output even when total sustainable

catch is similar. For MSE purposes, internal consistency is more important than imposing SS3 reference points on a structurally different simulator. Performance statistics should therefore use the FLBEIA-compatible reference points for each OM, with SS3 values retained as an external consistency check.

4.3 Suitability of SPiCT for the management procedure

SPiCT reproduced the broad status trends and generated reference points similar in scale to those from the OMs. Its terminal F/FMSY estimate was close to one and within the reported OM interval. Its B/BMSY estimate was lower than the OM median, while absolute BMSY was higher than the OM range. Together, these results indicate that the relative status estimates can be operationally informative, although direct comparison of absolute biomass quantities requires care because the models represent different biomass components.

Despite these differences, the quantities most relevant for management procedure implementation were broadly consistent between frameworks. SPiCT estimated FMSY values close to the median OM estimates, and the resulting MSY was very similar to that obtained from FLBEIA. Furthermore, historical biomass estimates produced by SPiCT were broadly consistent with the OM spawning biomass trajectories. As a consequence, management quantities derived from the combination of biomass and FMSY would be expected to generate catch levels comparable to those obtained from the operating models and consistent with observed catches. This suggests that SPiCT provides a suitable basis for estimating stock status and supporting TAC calculations within a model-based management procedure.

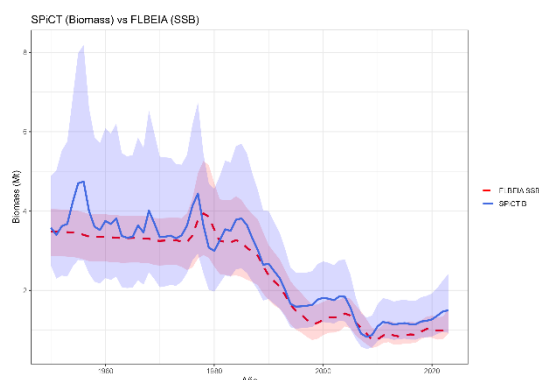


Figure 8. Historical comparison of exploitable biomass estimated by SPiCT and the SSB of the operating models.

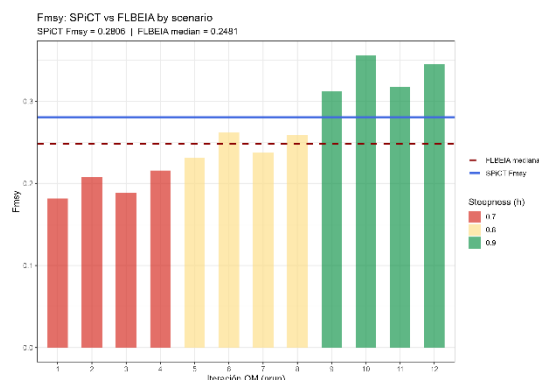


Figure 9. Comparison of F_{msy} estimated by SPiCT and the operating models.

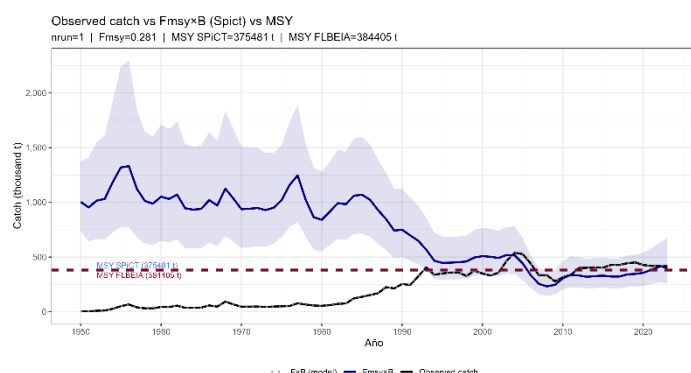


Figure 10. Historical comparison of catches estimated by $C_y=B_y \times F_{msy}$ and observed catches.

Although SPiCT did not converge for the split-index configuration, the unsplit index configuration converged successfully and provided stock-status estimates broadly consistent with the operating-model results. Since the intended management procedure is based on a single standardized CPUE series, the lack of convergence for the split-index configuration does not represent a major limitation. Instead, the results support the use of the unsplit index as a common observation series across the operating-model grid.

4.4 Implications for MSE development

The current operating-model grid provides a suitable foundation for the next stage of MSE development. The conditioning analysis demonstrated that the FLBEIA implementation reproduces the principal dynamics of the SS3 assessment and generates internally consistent reference points for simulation testing. The resulting 12-model uncertainty grid captures key assessment uncertainties related to CPUE treatment, catchability creep, and stock-recruitment steepness, providing an appropriate basis for evaluating candidate management procedures.

The preliminary analyses did not include recruitment variability or observation error, and future evaluations should incorporate these additional sources of uncertainty. The preliminary comparison with SPiCT suggests that a model-based management procedure using a single standardized CPUE series may provide stock-status estimates and reference points broadly consistent with those derived from the operating models, supporting its consideration in future MSE development.

Candidate management procedures should be tested across the full OM grid using conservation, yield, and stability performance metrics over short-, medium-, and long-term horizons. Performance should be summarised across all operating models and uncertainty factors to identify procedures that are robust to the alternative hypotheses represented in the conditioning framework.

4.5 Recommended next steps

- Introduce recruitment variability and observation error into the operating-model framework.
- Evaluate candidate management procedures across the full operating-model grid.
- Use FLBEIA-compatible reference points when evaluating management performance.
- Further investigate SPiCT as a stock-status estimator for a model-based management procedure.
- Consider incorporating additional sources of uncertainty if future analyses identify influential factors not currently represented in the operating-model grid.

5. Conclusions

Twelve operating models were successfully conditioned for Indian Ocean yellowfin tuna using FLBEIA and assessment information from SS3. The models reproduced the principal historical dynamics observed in the assessment and behaved coherently under a range of deterministic projection tests. FLBEIA-compatible reference points were broadly consistent with those estimated in SS3. Differences in MSY were generally below 10%, while larger differences in SSB_{MSY} resulted in systematic differences in relative biomass ratios, despite similar absolute biomass trajectories.

The comparison between SPiCT and the operating models showed that SPiCT was able to reproduce the broad historical trends in stock status and generated reference points of a similar scale to those obtained from FLBEIA. Historical biomass trajectories, FMSY estimates and derived catch levels were generally consistent with those from the operating models, suggesting that SPiCT may provide a suitable stock-status estimator for a model-based management procedure.

Although SPiCT did not converge when fitted to the split-index configuration, successful convergence of the unsplit index configuration supports the development of a management procedure based on a single standardized CPUE series across all operating models.

Overall, the operating-model framework developed in this study provides an appropriate basis for the next stage of Management Strategy Evaluation for Indian Ocean yellowfin tuna. Future work should focus on incorporating recruitment and observation uncertainty and evaluating candidate management procedures through closed-loop simulations across the full operating-model grid.

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