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Scoping the Next Generation of Tuna Stock Assessment Software: Progress Report (Project 123)

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1 Executive summary

The 3-year Project 123 aims to evaluate features and capabilities that will be important in future tuna assessments, explore fitting models to tuna data using existing software platforms, guide decisions on the type of new software development required, and establish collaboration with tuna Regional Fisheries Management Organizations (RFMOs) and research labs to achieve these goals.

At SC20, ISG-09 reviewed the scoping of next-generation tuna stock assessment software and supported prioritizing practical tasks, including transitioning swordfish and striped marlin assessments to Stock Synthesis and testing simplified models for yellowfin tuna. Members acknowledged the need to focus on immediate assessment priorities while keeping longer-term software development under consideration, depending on available resources and capacity. (SC20 Summary Report, Attachment E).

SC21 will review the progress of Project 123, which explores the transition to next-generation stock assessment software for tuna fisheries. The project report i) evaluates the benefits, limitations, uncertainties, and resource implications associated with each software platform under consideration; ii) evaluates the feasibility of analyzing tagging data independently from the main stock assessment models, a potential strategy to reduce model complexity while maintaining scientific robustness; and iii) identifies key analytical features and technical capabilities that future stock assessment platforms should incorporate, such as support for spatial structure, tagging integration, and flexibility for multi-species and multi-fleet assessments, to ensure that WCPFC assessments remain scientifically credible, transparent, and adaptable to evolving fishery and management needs.

SC21 will provide feedback on the progress of the project as needed.

We invite SC21 to:

- ~~note that over the next 5+ years, MULTIFAN-CL will begin to be phased out as a software platform for WCPFC tuna and billfish stock assessments;~~
- note that in 2025, the two billfish stock assessments, swordfish and striped marlin, transitioned from MULTIFAN-CL to Stock Synthesis;
- review and comment on two suggested software development work streams, described in this report, providing feedback that will guide the preparation of project proposal to be presented to SC22; and
- convene an ISWG to discuss the progress and develop activities and a TOR for the third year of Project 123.

2 Background

Following the retirement of the lead developer of MULTIFAN-CL (MFCL), Dave Fournier, future advances to the MFCL software are not expected to be as mathematically innovative as they were in the past. While this does not render MFCL obsolete in the medium-term, it flags the need to plan and identify whether alternative existing software exists, or new software must be developed in the longer-term, to continue to support the specificities and future requirements of WCPFC tuna stock assessments.

While MFCL (Fournier et al. 1998) continues to be improved to service the WCPFC tuna assessment needs over at least the next 5+ years, it is important to start on a phased approach to its replacement. An initial scoping phase is required to assess what features and capabilities will be important in future assessment software for tunas. This scoping phase will benefit from input from stock assessment scientists across global tuna RFMOs. Once this scoping phase is conducted, consideration of available software packages in relation to the desired features and capabilities can be conducted. This may identify suitable existing software that has potential to provide the desired features and/or has potential to be developed further. Alternatively, it may indicate whether embarking on development of a new software package is recommended.

There has also been discussion around the need to explore, through modeling/simulation exercises, the benefits of applying alternative assessment structures (i.e., length-age structured versus the traditional length-based age-structured approach of MFCL and Stock Synthesis) before embarking on major software developments or changing methodology. Similar can be said about exploring benefits of state-space models and their use of random variables. Simulation exercises to explore the benefits or drawbacks of alternative model structures or approaches will also require collaboration across tuna RFMOs and practitioners experienced in using the alternative approaches and/or software.

An important outcome of this work would be to ultimately have a software package that has the desired functionality for tuna assessments, not only for WCPFC but also for other tuna RFMOs, thus creating a user community and ongoing development support capacity, so as to avoid the current situation we are facing with MFCL. Wider collaboration in this venture is essential to achieving this and is expected to be encouraged through this project.

2.1 TOR summary

The project terms of reference established at SC20 are listed in Table 1.

Table 1. Terms of reference established at SC20, guiding the project activities conducted from August 2024 to August 2025.

TOR	Description
1	Review and identify a list of necessary features for software to do tuna stock assessments and identify existing software platforms that have these features or capacity to develop these.
2	Conduct two workshops with selected experts from other tuna RFMOs and/or with relevant expertise. The first workshop can be remote (prior to SC20) and the second one potentially in person (post SC20). The main goal will be to communicate the scoping project, upcoming model explorations, and succession plans for MFCL and Stock Synthesis, to seek advice from the scientific community, and to seek collaboration with tRFMOs and various research labs.
3	Explore the new RTMB programming environment and how it could be used in future tuna assessments. Specifically, how to modularize and organize code in RTMB models, on one hand code that is specific to one assessment and on the other hand code that is shared between assessments.
4	Establish collaboration with NOAA scientists to explore the feasibility of enhancing the tagging module in Stock Synthesis, making it more similar to the tagging module in MFCL.
5	Provide support to the stock assessment team transitioning the 2025 swordfish assessment from MFCL to Stock Synthesis. Also, coordinate with the 2024/2025 striped marlin assessment team to start preparing for the transition of that assessment to Stock Synthesis in 2029.
6	Compare a variety of software platforms using a simplified single-region WCPO yellowfin tuna dataset. The comparison will evaluate available features, run time speed, auxiliary tools, time and skills required to develop and diagnose models, and other characteristics.
7	Prepare alternative workplans and budget scenarios for the larger implementing (main) project to go beyond scoping. The scoping project will be expected to transition into the main implementing project based on the discussions at SC21, budget considerations, and funding availability. It is expected that the work leading up SC21 will inform the implementing workplan options and budget estimations.
8	Communicate with tuna RFMOs and other research labs to establish which RFMOs and labs are willing and able to commit scientist time to collaborate on specific tasks of the scoping project, as well as the upcoming main project.
9	Communicate with tuna RFMOs and the FIMS project team to evaluate whether joint software development by tuna RFMOs could produce FIMS code modules, with the aim to develop future tuna assessment models using FIMS modules.

3 Progress against TOR items

This section describes the project activities in the last 12 months from August 2024 to August 2025, as they relate to terms of reference 1–9 that were established at SC20.

3.1 TOR work area 1 (2024 second half)

> Review and identify a list of necessary features for software to do tuna stock assessments and identify existing software platforms that have these features or capacity to develop these.

A question was raised at SC20 about whether it would be possible to present a review and evaluation of necessary software features and existing software. This is provided below in one section covering software features and another section covering existing software.

3.1.1 Evaluation of necessary software features

Software features listed at CAPAM 2019 workshop

The CAPAM 2019 Workshop on Next Generation Assessment Models produced a review paper (Punt et al. 2020) that identifies a number of model features considered important in future stock assessment software. The abstract of the review paper lists these features:

- Ability to to capture age and size dynamics simultaneously yet computationally efficiently, while also offering the option to run a model as purely age-structured for a simple and fast model
- Scale from data-rich to data-poor
- Include some multispecies capability
- More appropriately deal with temporal variation, e.g., random effects and state-space models
- Better handling of tagging data, e.g., release-conditioned or recapture-conditioned model
- Ability to use close-kin mark-recapture data
- Efficient methods to share parameter priors among stocks, borrowing information from similar stocks where more data have been collected
- Training programs and documentation
- Data entry system that is well documented
- Does not require specification of inputs that will not be used in an application
- Expert system to configure default settings based on best practices
- Automatic production of diagnostic statistics

The summary table in Punt et al. (2020) adds the following features:

- Spatial structure
- Multiple fisheries and surveys
- Flexible parametrization of the initial conditions
- Multiple time steps within a year
- Flexible parametrization of growth
- Flexible parametrization of natural mortality
- Flexible parametrization of fecundity
- Flexible parametrization of movement
- Multiple recruitment functional forms, including nonparametric
- Selectivity as a function of age, size, or both
- Multiple selectivity functional forms, including dome-shaped and asymptotic
- Incorporation of ageing error
- Ability to simulate datasets for management strategy evaluation
- Prefer statistically based likelihood weighting over subjective choices
- Ability to evaluate uncertainty using a variety of statistical methods
- Allow time-varying processes, both in biology and fishing processes

Further in the text, Punt et al. (2020) add the following features:

- Allow for density-dependence at the spatial area level, as well as at the stock level
- Allow for nesting of spatial scales such that a population model can appropriately utilize data types collected at fine scale and coarse spatial resolutions
- Allow for multiple movement types including advection, diffusion, and that movement responds to environmental drivers
- Account for multiple hypotheses regarding movement, including age- and sex-specific processes processes, as well as density-dependent and time-varying movement

Software features listed at International Expert Meeting 2024

At the launch of this scoping project in 2024, an international expert meeting was held in two sessions. As a background for the meeting discussion, the conveners (Magnusson and Davies 2024) highlighted model features that can be especially relevant in tuna assessments:

Incorporating data

- Fit to length comps
- Fit to weight comps
- Fit to tagging data
- Fit to close-kin mark-recapture (CKMR) data
- Estimate growth curve using otolith data
- Utilize tag-recapture growth increment to estimate growth

Specifics

- Age-specific M
- Length-specific selectivity
- Sex-specific growth and M
- Region-specific growth

Dimensions

- Explicit regions with movement
- Tracking age and length in population
- Time steps within a year

Ecology

- Multispecies interactions
- Climate change

Implementation

- Random effects, state space
- Parallel computing
- Computation time

Software features: Conclusion

As reflected in the software features identified at CAPAM 2019 and the International Expert Meeting in 2024, there is a multitude of wish list options for technical features in stock assessment software. No software will provide all of these features, and the relative importance of individual features will vary between stocks. For example:

- The South Pacific albacore stock assessment will require the ability to incorporate close-kin mark-recapture (CKMR) data.
- The Western and Central Pacific Ocean (WCPO) skipjack stock assessment relies heavily on tagging data and should therefore employ the state-of-the-art statistical techniques for analyzing tagging data that are available at any time.

The best choice of a software for a given stock assessment will not only depend on the precise features provided by each software, but also how well each software allows the stock assessment team to work effectively to explore and develop models to produce a high-quality assessment in the time frame between the availability of data and the SC deadline for submitting the assessment report.

The conclusion of this scoping project is that the critical softure requirements for the WCPFC tuna and billfish assessments are best encapsulated in three general criteria:

1. *Scientific quality.* The software should have good statistical performance, demonstrating a low level of estimation bias in self-test simulations. It should make good use of available data, incorporating all relevant information in a statistically sound manner. It should also allow spatial and temporal variability in processes relating to the biology and the fishery dynamics. The software should be computationally efficient and produce a fitted model within too many hours, thus allowing a full exploration of a variety of model options in the short stock assessment time frame. Finally, the software should support the provision of scientific advice that matches the needs for the management of each stock.

2. *Beginner friendly.* New ~~staff scientists~~ are often asked to start working with the stock assessment software within their first twelve months of contract. To make this feasible, the software user interface and auxiliary tools should allow new staff scientists to have a good understanding of the configuration of model options and be able to work efficiently with the model.

3. *Widely used.* SPC does not want to use stock assessment software in isolation. The software should have a ~~large~~ development team and user community beyond SPC. This will mean that new staff scientists can find expert help outside of SPC. Feature-complete tools for working with model input and output will be maintained outside of SPC. By adopting widely used stock assessment software, external reviewers will have a good understanding of model configurations and options.

3.1.2 Evaluation of existing software

Stock Synthesis

Stock Synthesis (SS3) is used in tuna assessments by the IATTC, IOTC, and ICCAT, as well as in WCPFC billfish assessments as of 2025. Compared to MFCL, SS3 has a less sophisticated statistical method to analyze tagging data, which requires the scientist to convert length-at-release to age-at-release outside the model. This is especially relevant for the WCPO skipjack assessment. The SS3 development team does not plan to add new major features such as the ability to incorporate CKMR data, which is especially relevant for future South Pacific albacore assessment. On the other hand, the ~~increasing~~ use of SS3 at SPC has had a ~~marked~~ positive impact on collaboration between the tRFMOs, which is relevant for the discussion, development, and tests of future software. The use of SS3 also shortens the training time for new SPC stock assessors and makes their skills and experience more transferable between workplaces. SS3 assessments allow closer comparisons of assessments conducted across RFMOs and ISC. The large SS3 user community is relevant for seeking expert insights, discussing technical model decisions, and for peer reviews. It also comes with an exceptionally complete suite of tools useful for diagnostics, as well as automated plots and tables for assessment reports. See the proposed workshop on modeling techniques (Section 5.2)

Stock Synthesis scores particularly high in two key criteria: the ability of new staff scientists to use it effectively and the worldwide user community, including tuna RFMOs.

Gadget

Gadget 3 is the latest version of Gadget stock assessment platform, implemented in TMB. It is an age-length structured platform and the implementation of this software in TMB has resulted in a significant performance gain in terms of computational time, and opens the option of incorporating time-varying processes using random effects. Gadget has a wide range of features relevant for tuna assessments and a plan is underway ~~to~~ to test the use of Gadget on SPC example tuna datasets.

Gadget scores particularly high for representing certain state-of-the art statistical methods of interest: explicit age-length structure and a TMB implementation that may allow the use of random effects to have processes vary with time and/or between regions. See proposed analysis (Section 5.5).

SBT

The SBT software is used in the assessment of southern bluefin tuna by CCSBT. The software is implemented as an R package based on RTMB and stands out as the primary stock assessment software that is built around CKMR, a new and important data type in future South Pacific albacore assessments. The SBT package is designed for a single-region assessment and would require some additional development to be used for a multiregion assessment. The scoping project has reached out to the team of scientists involved in the SBT assessment and will discuss further the possibility of using their model code as a starting point for developing new software for the South Pacific albacore assessment. See the proposed SPC-CCSBT communication (Section 5.4).

SBT scores particularly high for incorporating CKMR data in a tuna stock assessment.

FIMS

Fisheries Integrated Modeling System (FIMS) is a NOAA project that coordinates the development of a next-generation framework of stock assessment models based on TMB. The initial FIMS development and case studies have focused on models fitting to age composition data, but the design includes the ability to fit to length composition data. Spatially explicit models and tagging data are currently not high priorities for the FIMS project. However, FIMS aims to provide a modular and flexible design paradigm, allowing scientists to choose and link together code modules to produce a stock assessment model that is tailored for a particular assessment. For the purposes of tuna assessments, it might be possible to design and develop specific code modules to link with the FIMS core modules. Such tuna modules could potentially provide a variety of features, adding basic model extensions and/or introducing underlying changes in the model structure.

FIMS is at a relatively early stage of development, but it scores high for its potential to become the foundation of mainstream stock assessment software. It is possible that many stock assessments using Stock Synthesis today will migrate to FIMS software in the future.

Other

Casal 2 is the latest version of the Casal stock assessment platform, rewritten with an improved design and user interface. Casal has a wide range of features relevant for tuna assessments. However, its strengths and features fall slightly short of Gadget 3 for the purposes of this scoping project.

3.2 TOR work area 2 (2024 second half)

> Conduct two workshops with selected experts from other tuna RFMOs and/or with relevant expertise. The first workshop can be remote (prior to SC20) and the second one potentially in person (post SC20). The main goal will be to communicate the scoping project, upcoming model explorations, and succession plans for MFCL and Stock Synthesis, to seek advice from the scientific community, and to seek collaboration with tRFMOs and various research labs.

Two workshops were conducted in 2024.

Workshop 2024 I: International Expert Meeting 2024

This remote workshop was held in two sessions on 13 May and 18 June 2024, inviting stock assessment and software development experts from around the world. Around 40 participants represented the tuna RFMOs (CCSBT, IATTC, ICCAT, IOTC, WCPFC), stock assessment software projects (ALSCL, CASAL, FIMS, Gadget, MFCL, SAM, sbt, Stock Synthesis, WHAM), and relevant programming environments (ADMB, TMB, RTMB). The objectives, format, and outcomes from this workshop were reviewed in the P123 progress report presented to SC20 in August 2024.

Workshop 2024 II: Project Strategy and Evaluation of Options

This workshop was held 23–30 August 2024 in Matapouri, New Zealand, with two in-person participants Arni Magnusson and Nick Davies, reaching out to Chris Cahill and Lisa Chong (Michigan State University), and Jeremy McKenzie (NZ). The following focus topics were covered in the workshop:

- Needs and options for future SPC tuna and billfish assessments
- Multi-criteria decision making: scientific quality, beginner friendly, widely used
- FIMS could be the only option that can score high in all criteria
- Tuna RFMOs could collaborate and develop tuna-specific FIMS modules
- Age-length structure, possible simulation study to examine potential importance
- Gadget as the main platform using age-length structure
- RTMB is a new and efficient paradigm, but both FIMS and Gadget use TMB
- RTMB code design, modularity, maintenance, reusing code in different assessments
- Sparse matrix calculations, parallel computations
- MFCL tagging module, each release group becomes a parallel population

Conclusions from the Matapouri workshop served as a basis for evaluating the necessary software features and existing software (TOR 1).

In particular, identifying the three general criteria for selecting stock assessment software (scientific quality, beginner friendly, widely used) made it clear that the choice of software is a case of multi-criteria decision making, where it may not be possible to optimize all three criteria.

The workshop notes and report are available on the scoping project website, along with analytical scripts and results.

3.3 TOR work area 3 (2024 second half)

> Explore the new RTMB programming environment and how it could be used in future tuna assessments. Specifically, how to modularize and organize code in RTMB models, on one hand code that is specific to one assessment and on the other hand code that is shared between assessments.

An initial evaluation of how RTMB code can be modularized and organized was conducted as part of the 2024 Matapouri workshop, where scientists at Michigan State University shared their recent reorganization of RTMB stock assessment case studies.

Modular design

The RTMB evaluation was resumed in December 2024, as part of a WCPO skipjack growth study, converting TMB scripts to RTMB scripts. Growth curve estimation using otoliths and tagging data is a simpler analysis than a full stock assessment, but the workflow involves the same types of code:

1. Model source code
2. User code to prepare data in the model-specific format
3. User code to specify model options
4. User code to run model
5. User code to read the results into tables

In TMB, the separation is very clear, with the model source code written in a C++ file, while the user code is organized in one or more R scripts.

In RTMB, the separation can be less clear, since the model source code is written in R. The example models that come with the RTMB package make a point of interweaving the model source code with the user code in one monolithic script. This is effective for demonstrating how much simpler the model source code is in RTMB than in TMB, but for developing and maintaining larger models it is useful to follow a modular design with a clear division between the general model source code and the specific user application.

In the skipjack growth study, three tiers of modular organization were tested and evaluated in RTMB. In the first tier, all code was interwoven in one script. In the second tier, the model source code was saved in a separate R file and then sourced into the user script. In the third tier, the model source code was encapsulated in an R package that becomes a general method for any species, thus completely separating the model from the specific skipjack growth study.

Developing a general model in RTMB requires a workaround in the form of a special wrapper to pass a data object to the model. This subject was raised on the RTMB discussion board in 2024 and resolved with a documented example added to the package vignette later that same year.

CRAN package

Having developed a general tool to estimate growth curves, it was decided to share the fishgrowth package with the wider scientific community in February 2025 by releasing it on CRAN (Magnusson and Maunder 2025). The package allows scientists to fit growth curves to otoliths and/or tagging data, choosing from five functional forms (von Bertalanffy, Richards, Gompertz, Schnute Case 3, growth cessation), with each functional form offered using alternative parametrizations.

Linking packages

As a follow-up to explore the ability to link RTMB packages, an additional package linear was also implemented, adding one more functional form of a growth model, different from the ones provided by the fishgrowth package. In this experiment, we first add the linear package as a dependency to the fishgrowth package and then create a new function called `experiment()` inside fishgrowth that calls the linear functional form. In short, the contributed growth curve was fitted successfully and the integration between the two modules was seamless.

The outcome of this experiment was to demonstrate that it is trivially easy to contribute additional functionality to an existing RTMB package. This experiment is analogous to contributing a tuna-specific code module to link with FIMS core packages, except FIMS is currently based on TMB rather than RTMB. The scoping project is currently reaching out to collaborate with FIMS to explore the technical procedures and programming interface involved in producing code modules that can be linked with FIMS core modules. The expectation is that contributing and linking code modules is more difficult in the FIMS/TMB paradigm than in RTMB, but hopefully not much more difficult. See the proposed SPC-FIMS workshop (Section 5.6).

Comparison between TMB and RTMB

Kasper Kristensen (DTU) released the TMB package on CRAN in 2015. It provides the same automatic differentiation capability for parameter estimation as ADMB, but with greatly improved functionality and performance when using random effects. The developer writes the model source code in written in C++ while user scripts are written in R.

Kasper Kristensen released the RTMB package on CRAN in 2023. It uses the underlying TMB engine to fit models, and the resulting model output and computational speed is the same as in TMB. The main difference is that in RTMB, the model source code is written in R, which has several important benefits. The code becomes substantially shorter and easier to understand, modify, and debug. There is no C++ compilation lag while developing a model, and it is easy for an RTMB package to provide many models rather than one. Linking code between RTMB modules, in the form of packages and/or scripts, is also easier than in TMB.

When the scoping project reached out to the team of statisticians at DTU to discuss the differences, they recommended writing all new modeling software in RTMB rather than TMB, citing the benefits listed above. To strengthen the longevity and usefulness of the SBT stock assessment model, it was ported from ADMB to TMB and more recently to RTMB, which makes the software easier to maintain and develop further. This does not mean that all current software projects should be ported to RTMB, but for developing new software it is the recommended programming environment.

3.4 TOR work area 4 (2024 second half)

> Establish collaboration with NOAA scientists to explore the feasibility of enhancing the tagging module in Stock Synthesis, making it more similar to the tagging module in MFCL.

To conduct this feasibility study, the scoping project reached out to Nicholas Ducharme-Barth (NOAA PIFSC) and Mark Maunder (IATTC), while also studying the MFCL code for analyzing tag releases and recaptures. The initial findings were that the tagging 'module' in MFCL is not an independent component that is easily extracted from the code, but is interwoven in the overall design of MFCL.

The way tagging data are handled in MFCL is that each release group produces a parallel population, so when there are multiple tag releases year after year, the model keeps track of a growing number of parallel populations. After a certain number of years following a tag release, the release group enters a pooled population of old releases, thus avoiding the need to track an unnecessarily large number of parallel populations. More detailed commentary on the tagging module in MFCL can be found in the day1.md notes from the 2024 Matapouri workshop.

The conclusion was that enhancing Stock Synthesis to apply the same statistical method would be a major undertaking and will not be pursued as part of the scoping project.

In discussions related to this TOR, Mark Maunder pointed out that IATTC has recently had good success analyzing the tagging data externally, rather than inside the stock assessment model, and recommended investigating this option for WCPFC assessments that involve tagging data. See the resulting SPC-DTU 2025 workshop (Section 4.1).

3.5 TOR work area 5 (2025)

> Provide support to the stock assessment team transitioning the 2025 swordfish assessment from MFCL to Stock Synthesis. Also, coordinate with the 2024/2025 striped marlin assessment team to start preparing for the transition of that assessment to Stock Synthesis in 2029.

A decision at SC20 was to transition the Southwest Pacific swordfish assessment to the Stock Synthesis software in 2025. In a January 2025, a joint SPC-NOAA striped marlin stock assessment modeling workshop concluded that it would be best to also transition the Southwest Pacific striped marlin assessment to the Stock Synthesis software in 2025.

The support provided by members of the scoping project for these two billfish assessments has been of the same nature as the teamwork behind all SPC stock assessments. This has involved daily discussions and weekly meetings reviewing the work in progress, providing code to configure multiple variations of the model to run in parallel, analysis of an alternative growth curve from otolith data, contributing to the report writing, etc.

The most valuable support for the two billfish assessments, however, came from international colleagues. Mark Maunder and Nicholas Ducharme-Barth provided key insights and improvements in the model configuration for these assessments. Furthermore, when the stock assessors posted questions on the general Stock Synthesis online forum, many scientists responded and shared their experiences, ideas, and recommendations that have directly helped with these assessments.

Transitioning these assessments to Stock Synthesis has been a learning process that requires new knowledge, tools, and technical solutions. The increased interaction with the wider scientific community has already proved to be an important benefit from using a widely used software platform for these assessments. See the proposed tuna RFMO workshop to review Stock Synthesis modeling techniques (Section 5.2).

3.6 TOR work area 6 (2025)

> Compare a variety of software platforms using a simplified single-region WCPO yellowfin tuna dataset. The comparison will evaluate available features, run time speed, auxiliary tools, time and skills required to develop and diagnose models, and other characteristics.

Work on this TOR involves a few steps:

1. Prepare a single-region yellowfin tuna (YFT) dataset
2. Develop a MULTIFAN-CL model to fit to the single-region YFT dataset
3. Develop models based on other software for comparison

The first step was relatively straightforward. The only difference between the original five-region dataset and the simplified single-region dataset is that the five CPUE indices are combined into a single index. The original dataset is available online on the yft-2023-diagnostic repository, both in MFCL and TAF format. The single-area CPUE index is available on the yft-2025-single-region repository.

The second step is presented in Appendix A. The model was developed using MFCL having no spatial stratification (a single region), while retaining the original fisheries definitions for the 32 capture fisheries, and their fishery-specific input data structures. Instead of the five region-specific survey fisheries for which CPUE indices were available, the simplified model defined a single survey fishery representative of the entire model domain. The simplified model was fitted and achieved convergence, and a comparison with the original multi-region model is included in the Appendix.

The third step will require a considerable amount of work and establishing a collaboration with a team of scientists who are domain experts in the use of a particular stock assessment software. Which software will be included in upcoming tests and comparisons will depend on prioritization by SC and the members of the scoping project, as well as the availability and interest of international colleagues. See the proposed Gadget model development (Section 5.5).

3.7 TOR work area 7 (2025)

> Prepare alternative workplans and budget scenarios for the larger implementing (main) project to go beyond scoping. The scoping project will be expected to transition into the main implementing project based on the discussions at SC21, budget considerations, and funding availability. It is expected that the work leading up SC21 will inform the implementing workplan options and budget estimations.

The scoping project has identified three streams of development work that could produce software to use in future WCPFC tuna and billfish assessments:

1. DTU spatio-temporal model
2. FIMS tuna-specific modules
3. IATTC designed tuna model

As of mid 2025, the first two of these software projects are under development, while the third model is a current design concept. All three have the potential to be used in future tuna stock assessments. The scoping project recommends for the work period from August 2025 to August 2026 that SPC work with DTU, FIMS, and IATTC to evaluate and examine the options further, as the scoping project works towards a development project proposal.

Discussion at SC21 will focus on the scientific value, uncertainties, and practical aspects of this upcoming development work, as it relates to future tuna and billfish stock assessments. The development project proposal will be presented at SC22 as a key outcome from the scoping project (see Section 5.7).

As an initial estimate, the development project could be launched as a three-year project from 2027 to 2030, with an annual budget of $200,000. This would allow:

- $50,000 per year for workshops and smaller development subprojects, in the same manner as the current scoping project; and
- $150,000 per year to divide between the development options that will be prioritized.

3.7.1 DTU spatio-temporal model

Background

The SPC-DTU 2025 workshop (Section 4.1) initiated a collaboration between SPC and statisticians at the Technical University of Denmark (DTU), Tobias Mildenberger and Anders Nielsen, to apply a spatio-temporal model to analyze tuna tagging data. The workshop and subsequent discussions have focused on WCPO skipjack tagging data and using the spatio-temporal model to produce abundance indices that can be used in any stock assessment software. The DTU team had earlier collaborated with IATTC on analyzing EPO skipjack data (Mildenberger et al. 2024), where abundance indices coming from the external tagging data analysis were successfully incorporated in the 2024 stock assessment of EPO skipjack tuna (Bi et al. 2024).

The earlier EPO skipjack analysis had been carried out using bespoke TMB scripts, but the DTU team is currently developing an R package (Mildenberger et al. 2025) that will be used to conduct the analysis of the WCPO skipjack data. The package is based on a newer RTMB framework and will be intended for general use to analyze animal migrations of aquatic and terrestrial animals, as well as birds.

As of mid 2025, the R package providing the DTU spatio-temporal model is under development. It can estimate preference functions that determine the effect of environmental variables on fish movement (Figure 1), but it does not yet have the capability to produce the abundance indices. The completion of the core features in the model software will be relevant for the possible follow-up development project described below.

Enhancing and extending the DTU spatio-temporal model

For the purposes of tuna assessments, the DTU spatio-temporal model currently serves as a useful tool for analyzing tagging data externally from the assessment model to produce abundance indices, which can faciliate transitioning tuna assessments from MULTIFAN-CL to other software.

When the earlier results from the IATTC-DTU analysis of EPO skipjack tagging data were presented and reviewed at the SPC-DTU 2025 workshop in Copenhagen, it was identified that improvements can still be made in the methodology. Areas that could be enhanced involve the use of effort data and the application of the Lincoln-Petersen mark-recapture estimator. During the initial exploration of fitting the spatio-temporal model to WCPO skipjack tags, it was also apparent that further development would be required to run the analysis using parallel computing, given the very large WCPO skipjack tagging dataset. Tagging data are known to be particularly influential in the WCPO skipjack assessment, which makes it important to ensure that the best available statistical methods are used to produce the resulting abundance indices.

Another development direction worth exploring is that the DTU spatio-temporal model could conceivably be extended considerably in the future, to become a full stock assessment model. This design concept was outlined by the DTU team at the 2025 workshop in Copenhagen. As a spatio-temporal model operating at a fine spatial scale, it currently keeps track of key quantities such as natural and fishing mortalities at each location. Thus, it already contains many elements of a stock assessment model, if processes such as recruitment and fitting to length composition data could be added. It is worth noting that the wider DTU team is responsible for designing and implementing the latest generation of models used in current European stock assessments, such as SAM and SPiCT. This means that their current speculations about extending the spatio-temporal model to become a full assessment model should be taken seriously and might become highly relevant for future tuna assessments. Unlike existing stock assessments, this would be a statistical framework

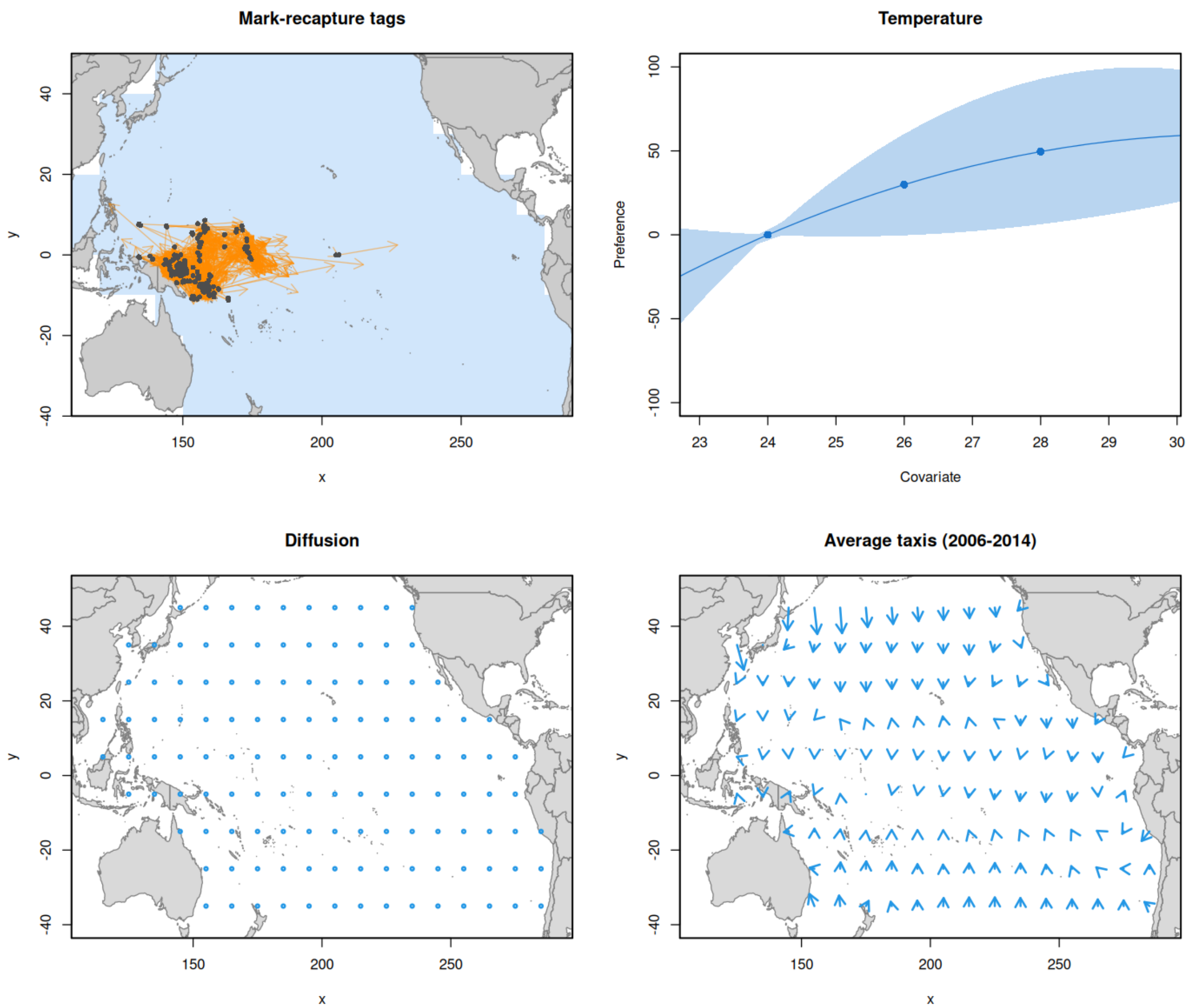

Figure 1. Snapshot of the DTU spatio-temporal model analyzing a small subset of the WCPO skipjack tagging data.

that incorporates movement, environmental variables, and other processes at a fine scale, rather than the somewhat arbitrary and very large rectangular regions used in today's tuna assessments.

A preliminary outcome of the current scoping project is to recommend funding the DTU team to enhance features and explore extensions of the spatio-temporal model, as described above. WCPFC funding of DTU research efforts into this new domain in fisheries science would make it more likely that operational stock assessment software would be successfully developed. Secondly, funding and collaboration would make it more likely that the resulting software would have the design focus and features that directly address the requirements of WCPFC tuna assessments.

As of mid 2025, it is too early to lay out a precise work plan for enhancing and extending of the spatio-temporal model. However, the latest development version of the R package is now close to having all the basic features of the model in place, which will complete the core foundation before work can start to further enhance and explore extensions of the model. The SC21 meeting is an opportune time to discuss the possible prioritization and funding of this work stream that can be formalized in 2026, a software development project focusing on enhancing and extending the spatio-temporal model. For this reason, we suggest that a small informal working group could be convened by the SC to discuss the potential scope, deliverables, timeline, and resources for this work stream, which has the potential to develop next-generation stock assessment software to be used in future tuna assessments.

The development work on enhancing and extending the spatio-temporal model would be carried out by the team of statisticians at the Technical University of Denmark, based in Copenhagen.

3.7.2 FIMS tuna-specific modules

Background

The FIMS project aims to provide a modular and flexible design paradigm, allowing scientists to choose and link together code modules to produce a stock assessment model that is tailored for a particular assessment. The project has currently developed a core module that allows the construction and fitting of simple age-structured models. Early FIMS exploratory case studies have focused on fitting to catch-at-age data, and the project is likely to initially prioritize the needs of NOAA stock assessments in U.S. waters.

For the purposes of tuna assessments, it might be possible to design and develop specific code modules to link with the FIMS core modules. Such tuna modules could potentially provide a variety of features, adding basic model extensions and/or introducing fundamental changes in the model structure.

Development of tuna-specific FIMS modules

Before starting work on the potential design and development of full-featured code modules, the first step will be to explore the technical procedures and programming interface involved in producing FIMS-compatible modules. This initial exploration should focus on very simple additions or model modifications as a demonstration. After the technical exploration of such prototype FIMS modules, the advantages and disadvantages of tuna-specific FIMS modules can be evaluated against other forms of tuna stock assessment software development. See the proposed SPC-FIMS workshop (Section 5.6).

A preliminary outcome of the current scoping project is to recommend the development of tuna-specific code modules that can be linked with core FIMS modules to produce a model that is tailored for tuna stock assessment. Possible examples of tuna-specific FIMS modules might provide some of the following features:

- Reference points specific for a tuna RFMO
- Improved handling of tagging data
- Explicit regions with fish movement coefficients
- Explicit age-length structured population array, rather than age only

As of mid 2025, it is too early to lay out a precise work plan for the development of tuna-specific FIMS modules. However, recent milestones reached by the FIMS project show that their software is now ready for a workshop focusing on the technical procedures and programming interface involved in producing FIMS-compatible modules. The SC21 meeting is an opportune time to discuss the possible prioritization and funding of this work stream, a software development project producing tuna-specific FIMS modules. For this reason, we suggest that a small informal working group could be convened by the SC to discuss the potential scope, deliverables, timeline, and resources for this work stream, which has the potential to develop next-generation stock assessment software to be used in future tuna assessments.

The development work on tuna-specific FIMS modules could be carried out by a consultant, working at SPC headquarters or remotely.

3.7.3 IATTC designed tuna model

The scoping project has regularly reached out to experts in tuna stock assessments to discuss development options for future tuna stock assessment software. In a recent discussion, Mark Maunder (IATTC) shared his perspective that there is a need for a new general model that can be applied in tuna stock assessments. In his words, there are structural design issues to be considered, such as:

- Spatial structure (e.g., fine scale spatio-temporal models)
- Length based dynamics
- Random effects
- Tagging data
- Close kin mark-recapture
- Multi-species

In his view, if he was asked to design a new model for tuna assessments today, this is what he would probably do:

- Large block spatial structure
- No length based dynamics
- Include random effects
- No tagging data
- Hopefully close kin mark-recapture can be added later easily
- No multi-species

This outline of a model design seems like an achievable model to implement, with a high probability of success. For the purposes of this scoping project, an initial evaluation of this model highlights the following key benefits:

- New codebase in RTMB that will be relatively small, easy to modify and extend
- Keeping it simple, just focusing on the priority needs of tuna assessments
- Random effects, useful for allowing processes to vary in time and possibly between regions

The design reflects the new paradigm adopted by IATTC to analyze tags using spatio-temporal analysis outside the assessment model. Given the growing importance of the ability to incorporate CKMR data in tuna assessments, a development project would take into account that this important model capability would be added as the next milestone after achieving the core functionality listed above. It is worth noting that the SBT stock assessment model that incorporates CKMR data started off as a model without this feature, which was added later (Rich Hillary, pers. comm.).

Mark Maunder has proposed organizing an online CAPAM workshop (Section 5.1) with tuna RFMOs and invited experts to discuss the structural components of this tuna model design.

3.7.4 Adaptive plan

Uncertainty and risks

It is important to acknowledge the inherent uncertainty around the evolution of next-generation stock assessment software. A general conclusion from reaching out to the scientific community is the consensus that one cannot reliably predict which of the current research and development directions will be most relevant and useful for future tuna assessments.

The proposed development work streams outlined above are subject to considerable uncertainty and risks:

- The DTU spatio-temporal full assessment model design might involve complexities and levels of detail that are beyond the available information in tuna assessments, where data are often sparse and subject to imperfect sampling. Even if successfully developed, such a model might not be estimable or practical as a basis for providing management advice.
- The FIMS project might work with an overly complex framework architecture that results in slower progress and lower levels of code contributions than anticipated. A possible outcome could be that FIMS software will not be used in future tuna assessments.
- The IATTC designed model resembles currently used models and has a lower level of uncertainty and risk than the other development options. It seems likely that this model could be used in future tuna assessments.

The recommended strategy to succeed in the face of uncertainty is to be active and adaptive. Being active means investing resources into collaborative research and development of new stock assessment methods and software. This will improve the general outcomes in terms of the quality of the science. Being adaptive means incorporating new scientific information and findings as they emerge and alter the direction accordingly.

Another part of a successful strategy towards transitioning the WCPFC stock assessments from MULTIFAN-CL will be to strengthen the partnerships with DTU and IATTC.

3.7.5 Partnerships

DTU as a key provider of model development

The scientific community regards the team of statisticians at the Technical University of Denmark (DTU) as a preeminent research group developing next-generation stock assessment methods and software. The programming environments TMB and RTMB, the state-space stock assessment models SAM and SPiCT, and the spatio-temporal model described above are only some of the examples where the DTU team has introduced new paradigms for how fisheries science is conducted.

The DTU team benefits from internal access to each other within the workplace. For example, during their initial development of their spatio-temporal model, Tobias Mildenberger and Anders Nielsen realized that the design of TMB was preventing them from using a certain computational approach. Discussing their findings with Kasper Kristensen, he identified a way to significantly alter and improve the overall design of TMB to support this type of computational approach. Other members of the DTU team include Casper Berg, Christoffer Albertsen, and Vanessa Trijoulet, with Anders Nielsen as the team coordinator.

IATTC as our closest collaborator

The best outcome for SPC would be to use stock assessment software that is also used outside of SPC. In practical terms, the software used by other tRFMOs will be especially relevant for identifying the best software for the WCPFC tuna and billfish stock assessments. Among the tRFMOs, IATTC has a particularly high research and development capacity and has a long history working closely with SPC researching stocks whose distribution often straddles the management boundaries between the WCPO and EPO. IATTC and SPC regularly collaborate in peer reviews and workshops to share ideas, experiences, and new methods for tuna and billfish assessments.

Given the benefits of using the same software as other tRFMOs, it seems sensible to coordinate, consult, and collaborate with IATTC when the time seems right to move a certain assessment from one software platform to another.

3.8 TOR work area 8 (2025)

> Communicate with tuna RFMOs and other research labs to establish which RFMOs and labs are willing and able to commit scientist time to collaborate on specific tasks of the scoping project, as well as the upcoming main project.

A list of ten questions was circulated to all the tuna RFMOs, to inform the scoping project about current and future tuna stock assessment software.

1. What assessment software do you use for tuna and billfish assessments? If possible, can you indicate which software is used for which stock?
2. Are these software adequate for your current needs?
3. Do you the think they will still be adequate in 10 years? If not, what are the likely main inadequacies?
4. How important is explicit regional structure for the assessment and management of tuna and billfish stocks for your RFMO?
5. Are tagging data important for any of your assessments? If so, which assessments?

6. Given that Stock Synthesis is entering a sunset phase, do you have a strategy or plans in place for a post Stock Synthesis era? If yes, can you provide a brief description of your strategy or plans?
7. How closely do you follow ongoing FIMS developments? Are you directly involved in discussions or experimental development?
8. Do you have any ongoing development work on improving existing stock assessment software or developing new software? If yes, can you provide a brief description?
9. Would you be willing to work collaboratively on the evaluation and/or development of software tailored for tuna assessments? If yes, is it likely that resources or scientist time might be available for this?
10. Would your team be interested in attending an online CAPAM workshop focusing on current and future development of new stock assessment platforms to meet the needs of future tuna assessments?

The responses from the tuna RFMOs are available on the project website.

In the response to question 9, regarding the ability to commit scientist time to collaborate in the development and testing of stock assessment software, the tuna RFMOs generally indicate a positive interest and emphasize the importance of collaboration between the tuna RFMOs.

3.9 TOR work area 9 (2025)

> Communicate with tuna RFMOs and the FIMS project team to evaluate whether joint software development by tuna RFMOs could produce FIMS code modules, with the aim to develop future tuna assessment models using FIMS modules.

In the response to question 7 in the above questionnaire, and more specifically in follow-up discussions, the tuna RFMOs indicate different views on the FIMS project. IOTC indicated that they had not been following the FIMS project, while IATTC and CCSBT have expressed reservations about the potential of FIMS to produce software relevant for future tuna assessments. Their recommendation is to develop new tuna assessment software in RTMB that could be used by the tuna RFMOs, rather than investing resources in producing FIMS-compatible modules.

The scoping project remains slightly more optimistic about the potential of FIMS to produce software relevant for future tuna and billfish assessments. After reaching out to the FIMS project, the conclusion from the discussion is to plan a joint workshop to explore the development of tuna-specific FIMS modules. See the proposed SPC-FIMS workshop (Section 5.6).

4 Other recent project activitites

4.1 SPC-DTU workshop to analyze tagging data

DTU workshop background

One challenge with transitioning tuna assessments from MFCL is that it is considered the best statistical implementation of incorporating tagging data in an integrated assessment model. Other software tend to use slightly less sophisticated methods for incorporating tags. When discussing this challenge with Mark Maunder (IATTC), he pointed out that in the 2024 EPO skipjack assessment, IATTC had good success analyzing the tagging data externally, rather than inside the stock assessment model. In this approach, a spatio-temporal model is used to analyze the tagging data to produce abundance indices, which are a basic input data type that can then be incorporated into any stock assessment model.

This spatio-temporal model (Mildenberger et al. 2024) is a recent innovative model that was developed by Tobias Mildenberger and Anders Nielsen at the ~~Technical University of Denmark~~ (DTU) in collaboration with Mark Maunder. After a round of discussion among the members of the scoping project, it was decided to fast-track and organize a technical workshop to explore the feasibility of using this modeling approach to analyze WCPO skipjack tagging data.

The workshop was held at DTU in Copenhagen 12–16 May 2025. Participants were Arni Magnusson, Joe Scutt Phillips, and Inna Senina from SPC, and Anders Nielsen and Tobias Mildenberger from DTU. Part-time attendees were Mark Maunder and Rujia Bi from IATTC (short online meeting) and Colin Millar from ICES. John Hampton contributed to workshop discussions via email during the week. The scoping project used the opportunity to reach out to the wider team of statisticians at DTU, discussing RTMB model development with Kasper Kristensen, Casper Berg, Vanessa Trijoulet, and Molly Brooks.

DTU workshop activities

With SPC and DTU presentations and discussions, we laid the foundation of a collaborative project to analyze the SPC tagging data using the DTU spatio-temporal model.

During the workshop, Tobias Mildenberger developed an early prototype demo model, using a small subset of the SPC tagging data. The model estimates a number of parameters describing the effect of environmental variables on movement, in the form of preference functions using splines (Figure 1). The prototype model developed during the workshop does not produce biomass indices, which is a subsequent step in the analysis. The preliminary analysis conducted during the workshop confirmed that the data are in the right format, ready for the upcoming analysis.

The workshop presentations, notes, and report are available on the scoping project website, along with analytical scripts and results.

DTU workshop follow-up

See the proposed follow-up project activity to support enhancing and extending the spatio-temporal model (Section 5.3).

5 Recommendation of project activities

5.1 Support online CAPAM workshop on future tuna assessment software

Mark Maunder has proposed organizing an online CAPAM workshop with tuna RFMOs and invited experts to discuss the structural components of a possible future tuna assessment model design (Section 3.7.3).

It would be beneficial for the scoping project to have an active support role in organizing and conducting this workshop. The timing of this workshop is to be decided.

5.2 Tuna RFMO workshop to review Stock Synthesis modeling techniques

Transitioning the two WCPFC billfish assessments to Stock Synthesis has been a learning process that requires new knowledge, tools, and technical solutions. The increased interaction with the wider scientific community has already proved to be an important benefit from using a widely used software platform for these assessments (Section 3.5). See also the overview and evaluation of Stock Synthesis (Section 3.1.2).

It would be beneficial for the billfish assessments and possibly future tuna assessments to bring together scientists who have experience and expertise in configuring and diagnosing tuna and billfish assessments in Stock Synthesis. SPC could organize such a workshop jointly with other tuna RFMOs. The timing of this workshop is to be decided.

5.3 Support DTU analysis of WCPO skipjack tagging data

The next step in the DTU analysis of WCPO skipjack tagging data is to secure funding for the DTU team to work on the spatio-temporal model development and analysis. The timeline of the project will be aligned with the 2028 WCPFC skipjack assessment, so the final model results should be delivered by the end of 2027. Intermediate milestones will be planned after funding has been secured, possibly organizing a second workshop to discuss and decide on model options.

See the SPC-DTU 2025 workshop (Section 4.1) for the work completed so far, as well as further details about the analysis, along with possible enhancements and extensions of the DTU spatio-temporal model (Section 3.7.1).

5.4 Explore the possibility of using the SBT model code

The scoping project has reached out to the team of scientists involved in the SBT assessment and will discuss further the possibility of using their model code as a starting point for developing new software for the South Pacific albacore assessment. IATTC is also involved in this discussion, as albacore is a joint assessment between WCPFC and IATTC.

See the overview and evaluation of the SBT stock assessment software (Section 3.1.2).

5.5 Develop Gadget model for single-area yellowfin dataset

The scoping project has reached out to the Gadget development team (Bjarki Elvarsson and Jamie Lentin) to explore the possibility of fitting a Gadget model to the single-area yellowfin dataset that was prepared as part of the scoping project (Section 3.6).

It would be beneficial for the scoping project to gain first-hand experience fitting a Gadget model to a large tuna dataset that consists of 280 quarterly time steps, 40 quarterly ages, 95 length bins, and 32 fisheries. This can help the scoping project gain insights from using an explicity age-length structured model to analyze tuna data and get a rough estimate of the computational overhead of age-length models. Gadget represents certain state-of-the art statistical methods of interest, and examining the model configuration, results, and diagnostics will be a useful reference for designing any future tuna assessment software. See the overview and evaluation of Gadget (Section 3.1.2).

5.6 SPC-FIMS workshop to explore linking FIMS modules

The scoping project has identified the usefulness of exploring the technical procedures and programming interface involved in producing FIMS-compatible modules. This initial exploration should focus on very simple additions or model modifications as a demonstration. After the technical exploration of such prototype FIMS modules, the advantages and disadvantages of tuna-specific FIMS modules can be evaluated against other forms of tuna stock assessment software development.

See the overview and evaluation of the FIMS project (Section 3.1.2), as well as the possible development work stream (Section 3.7.2). The timing of this workshop is to be decided.

5.7 Formal proposal for WCPFC software development project

This year's progress report outlines a potential development project, describing possible development work streams that are currently being evaluated (see Section 3.7).

The scoping and evaluation will continue for the work period from August 2025 to August 2026, with a formal development project proposal to be be presented at SC22 as a key outcome from the scoping project.

6 Updated project diagram

7 Note to SC

8 References

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A Appendix: Single-region YFT2023 model

Nick Davies
1 July 2025

Summary

As part of the P123 project "Scoping the next Stock Assessment software", a step includes the preparation of a simplified tuna stock assessment model and input data set. This report presents the preliminary results of this step using the yellowfin tuna stock assessment model as was developed in 2023. The original model was spatially stratified into 5 defined regions. A simplified version was developed using MULTIFAN-CL having no spatial stratification (a single region), while retaining the original fisheries definitions for the 32 capture fisheries, and their fishery-specific input data structures. Instead of the five region-specific survey fisheries for which CPUE indices were available, the simplified model defined a single survey fishery representative of the entire model domain. The simplified model was fitted and achieved convergence, and a comparison with the original multi-region model is presented here.

Method

The existing YFT2023 diagnostic case model that employs the catch-conditioned method was used for preparing the input data, and to demonstrate the application of MULTIFAN-CL to a spatially unstratified tuna data set.

De-stratification of the model spatial configuration and observations

The input files that specify the spatial stratification, recruitment and movement parameterisations (*.ini and *.frq) were duly modified to define a single region with no movement diffusion coefficients or spatial recruitments. All fisheries and all tagging release events were defined to occur in the same single region. All other fishery-specific observations (size compositions, catch, effort, conditional age-length data) for the capture fisheries (1 to 32) were retained without modification; as these fisheries were re-defined as occurring in the single region. A single standardized CPUE time series was available for the survey fisheries combined over all 5 regions, and was taken as being representative of the entire model domain, i.e., a single-region index. Similarly, the size composition data among all five survey fisheries were aggregated into a single data set. This single survey fishery (33) was defined as such for the simplified model. Estimates of temporal precision for the CPUE indices were available, allowing a concentrated CPUE likelihood to be estimated for the simplified model.

The initial MULTIFAN-CL -makepar operation was completed, and the resultant 00.par file structure was assessed for correctly excluding all spatial stratification or movement parameterisation. All phases of the doitall minimization that originally included spatial parameter estimation, were modified to de-activate the estimation of these parameters. The phase 1 operation was successfully completed, and then all subsequent phases of the minimization run to convergence.

The models included in this comparison were:

mult_regs	- original YFT2023 diagnostic case model, having multiple (5) regional strata
sngl_reg_cpue1	- simplified single-region model, employs non-concentrated CPUE likelihood
sngl_reg_conc_cpue1	- simplified single-region model, employs concentrated CPUE likelihood

Results

Both the single-region models produced stable minimisations with converged solutions obtained (maximum gradients ~2.0e-04). Whereas the multi-region model produced a positive definite Hessian (PDH) solution, neither of the single-region models were PDH solutions (Table 1).

In respect of the size-composition data, comparable fits to the length-frequencies were obtained among the models, but markedly worse weight-frequency fits were obtained for the single-region models (21% worse negative-log likelihood) (Table 1). Similarly, worse fits were obtained to the tagging data (9.6% worse negative-log likelihood). Slightly better (1.1%) fits were obtained to the conditional age-length data by the single-region models. There was negligible difference in the fit to the CPUE indices among the single-region models (Figure 8), with that using the concentrated likelihood differing only slightly in respect of the indices in the early time periods for which temporal precision was low.

There were notable differences in the recruitment and natural mortality estimates of the single-region models compared to the multi-region model. Absolute recruitments were approximately 50% lower in all time periods (Figure 2), but with similar temporal variation. The Lorenzen natural mortality function was lower overall by on average approximately 10%, which accorded lower mortality, particularly for age classes < 12 quarters (Figure 5). In contrast, the growth function was almost identical (Figure 4). A number of the estimated selectivity-at-age functions were more dome-shaped, or with lower right-hand limbs (Figure 6).

Despite these differences in model fit to the observations and estimated parameters, overall absolute biomass was generally similar among the multi- and single-region models (Figure 1), and showed similar temporal variation. Noticeable differences were however evident in the recent periods (the past 15 years), with absolute total biomass of the single-region models being 23% lower (Table 1). Despite this similarity, the estimated depletion of adult biomass is at a 35% lower level compared to the multi-region model (Table 1 and Figure 7). Equilibrium quantities also differed, with MSY being 9.5% lower, and unfished total biomass (B0) being 8.6% higher (Table 1).

These differences in the model derived variables can be attributed to the various parameter estimates that differ among the multi- and single-region models. It seems surprising that a model having substantially lower productivity (50% of the recruitments), yet sustains the equivalent total removals and produces a comparable absolute abundance, with only 10% lower equilibrium yield. Notably, the lower Lorenzen natural mortality over all age classes substantially reduces the total mortality; hence, B0 is higher. The more dome-shaped selectivities and being lower for older age classes, reduces fishing mortality for the older age classes and allows for "cryptic" biomass, and increases MSY. Also, the spatial dynamics of the multi-region model in respect of recruitment, movement and fishing mortality on sub-populations may increase the overall fishing mortality estimates. Whereas, the fishing mortality of all fisheries acting upon a single population serves to exclude the effects of high impacts on sub-populations.

The combined effects of the above parameter differences can accord higher resilience of the single-region model to fishing mortality. However, the lower natural mortality rate contributes to greater estimated depletion, indicating the relative fishing impact is higher. A closer examination of the estimated adult depletion within the equatorial regions of the multi-region model (regions 2, 3 and 4) reveals substantial regional differences, with that of region 2 being very similar to the estimated level of the single-region models. This might indicate a dominant effect of the region 2 observations upon the single-region model estimates.

Tables and Figures

Table A.1. Comparison of selected model parameters, negative log-likelihood terms and derived quantities, for the multi-region (mult_regs) and single-region models (sngl_reg_cpue1, sngl_reg_conc_cpue1).

Model quantity	mult_regs	sngl_reg_cpue1	sngl_reg_conc_cpue1	%diff_nonconc	%diff_conc
MSY	169700	153500	153600	-9.55	-9.49
Ccurr.MSY	4.224	4.665	4.662	10.44	10.37
Fmsy	0.073	0.060	0.060	-18.08	-18.08
Fmult	1.676	1.209	1.206	-27.86	-28.04
Fcurr.Fmsy	0.597	0.827	0.829	38.63	38.97
B0	8510000	9241000	9244000	8.59	8.63
Bmsy	2336000	2580000	2581000	10.45	10.49
Bcurr	4648625	3587013	3577813	-22.84	-23.04
SB0	5347000	6573000	6576000	22.93	22.98
SBmsy	1072000	1440000	1440000	34.33	34.33
SBcurr	2404755	1996569	1991219	-16.97	-17.20
Bcurr.Bmsy	1.990	1.390	1.386	-30.13	-30.34
SBcurr.SBmsy	2.243	1.387	1.383	-38.19	-38.36
SBcurr.SBcurrF0	0.454	0.296	0.295	-34.92	-35.08
SBlatest.SBlatestF0	0.429	0.292	0.291	-31.95	-32.15
obj_bhsteep	0.311	0.415	0.415	33.51	33.31
obj_lencomp	-154969.914	-153345.580	-153345.611	-1.05	-1.05
obj_wtcomp	-610342.171	-483274.416	-483273.668	-20.82	-20.82
obj_tagdata	13217.201	14479.783	14479.435	9.55	9.55
obj_agelngdata	2480.443	2452.738	2452.727	-1.12	-1.12
obj_cpue	-1157.645	-314.031	-313.991	-72.87	-72.88
Obj	-750515.800	-619859.458	-619858.965	-17.41	-17.41
No. parameters	1901	445	445	-76.59	-76.59
gradient	0.0001268	0.0001774	0.0001527	39.90	20.46
Lmin	19.800	19.800	19.800	0.00	0.00
Lmax	141.958	141.924	141.923	-0.02	-0.02
K	0.132	0.132	0.132	0.03	0.03
PDH	Yes	No	No	-	-

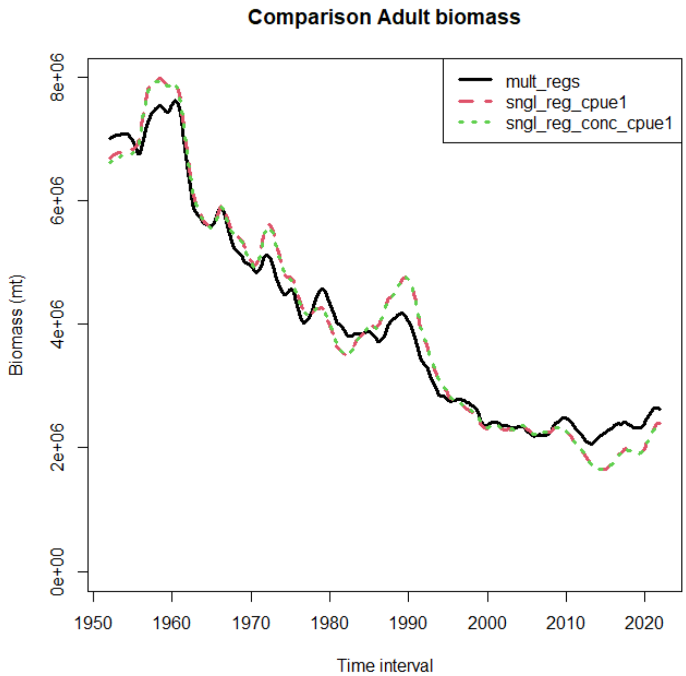


Figure A.1. Comparison of adult biomass between the multi-region (mult_regs) and single-region (sngl_reg_cpue1, sngl_reg_conc_cpue1) models.

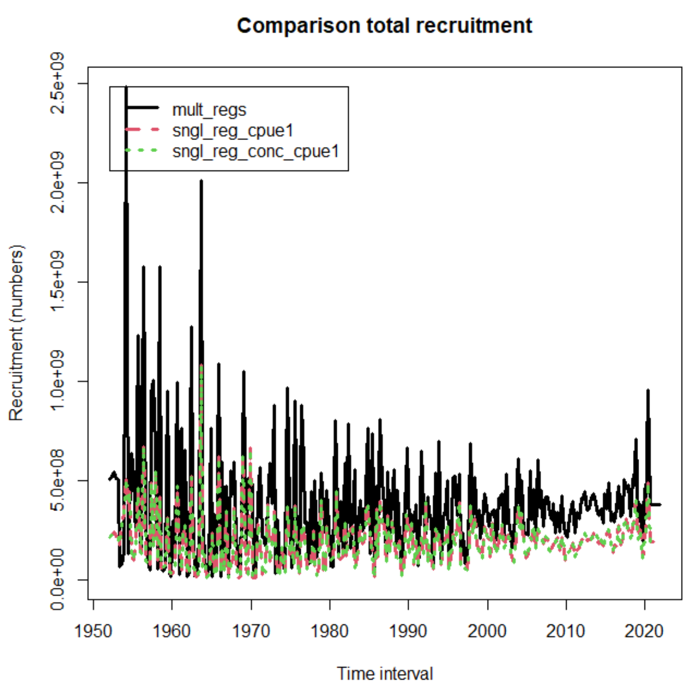


Figure A.2. Comparison of estimated absolute recruitment between the multi-region (mult_regs) and single-region (sngl_reg_cpue1, sngl_reg_conc_cpue1) models.

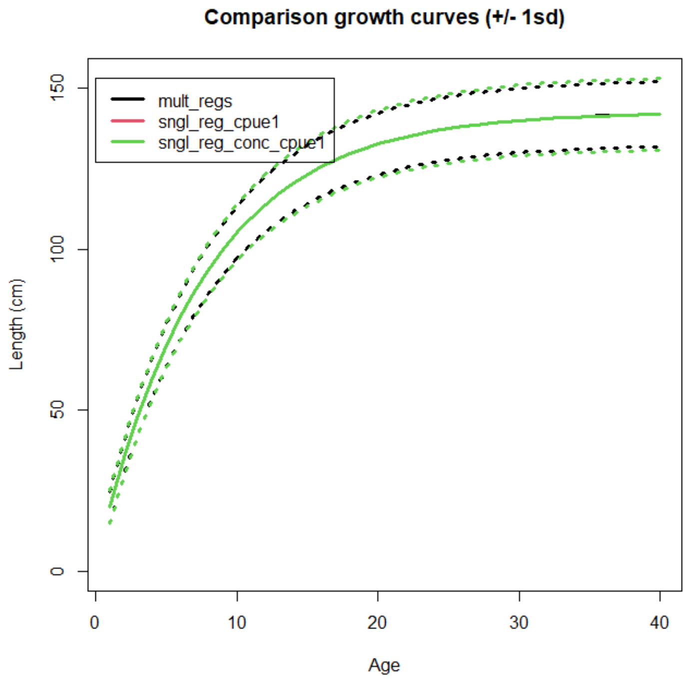


Figure A.4. Comparison of estimated von Bertalanffy growth between the multi-region (mult_regs) and single-region (sngl_reg_cpue1, sngl_reg_conc_cpue1) models.

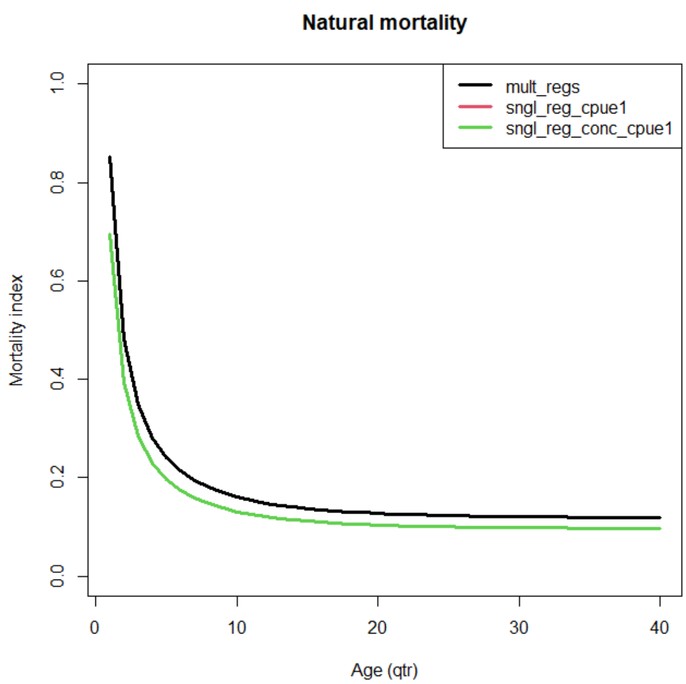


Figure A.5. Comparison of estimated Lorenzen natural mortality functions between the multi-region (mult_regs) and single-region (sngl_reg_cpue1, sngl_reg_conc_cpue1) models.

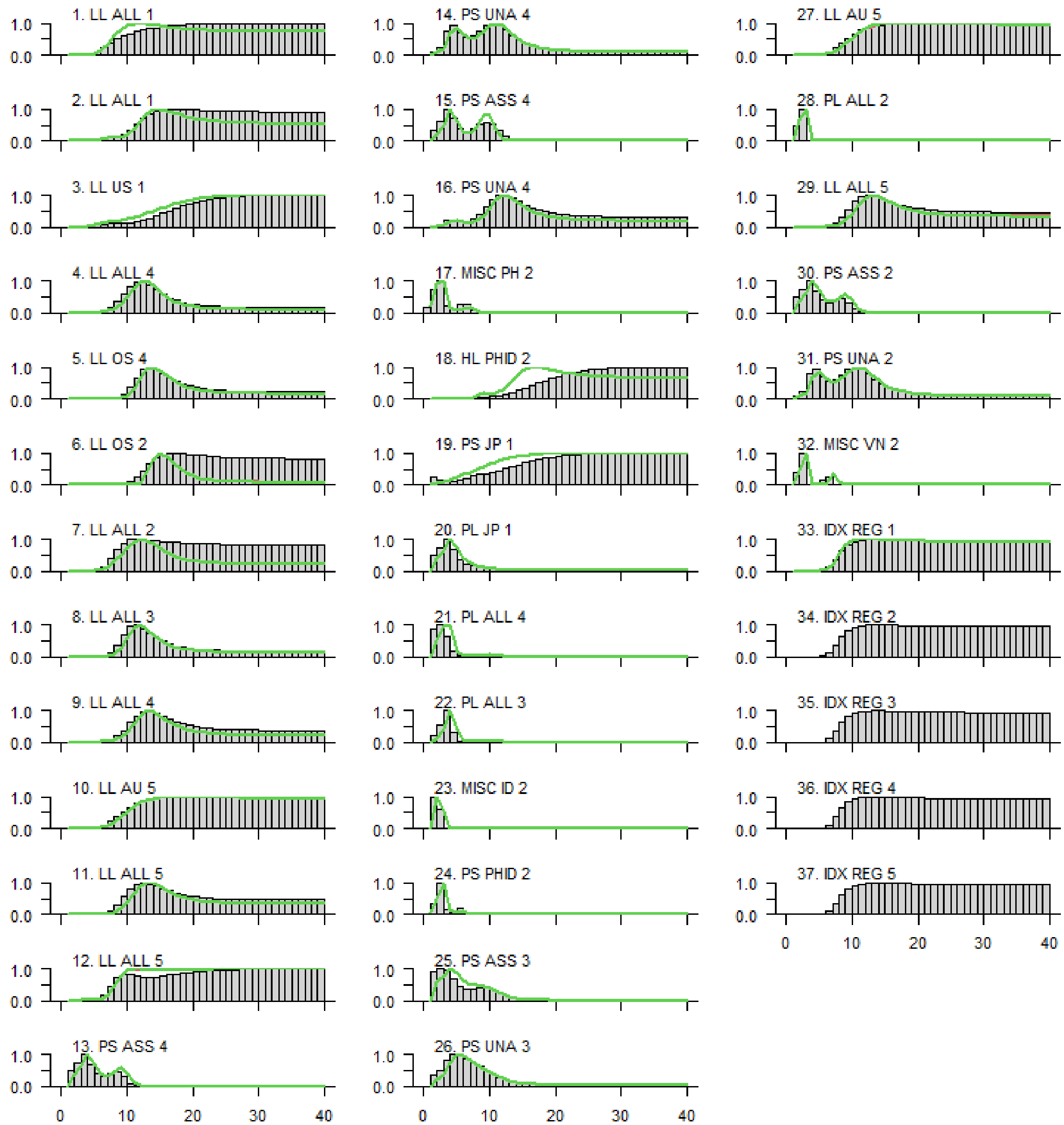


Figure A.6. Comparison of estimated selectivity-at-age between the multi-region (mult_regs, histograms) and single-region (sngl_reg_cpue1, sngl_reg_conc_cpue1, red and green lines) models.

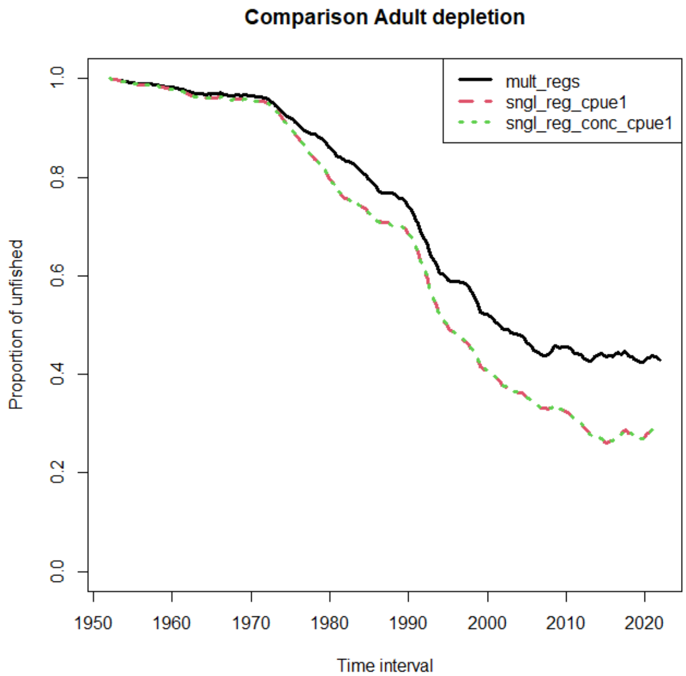


Figure A.7. Comparison of estimated spawning biomass depletion between the multi-region (mult_regs) and single-region (sngl_reg_cpue1, sngl_reg_conc_cpue1) models.

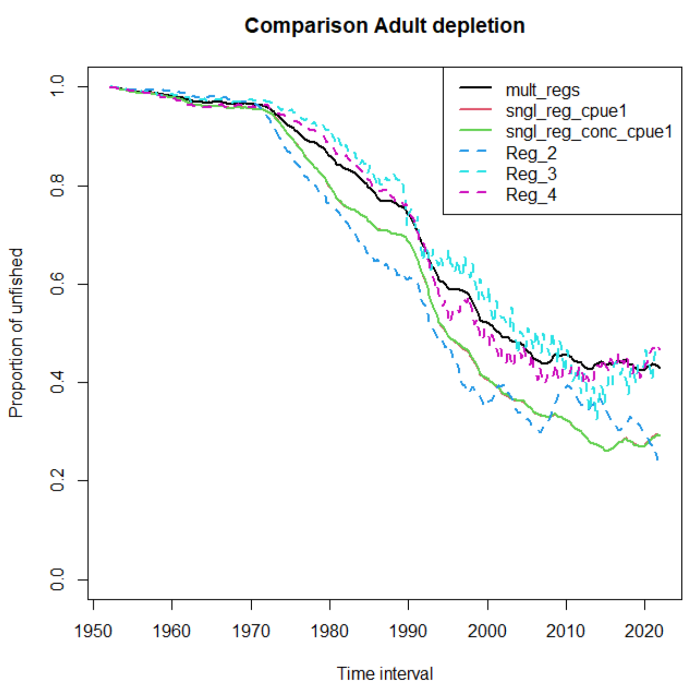


Figure A.8. Comparison of estimated spawning biomass depletion between component regions of the multi-region model (Region 2, Region 3, Region 4) and single-region (sngl_reg_cpue1, sngl_reg_conc_cpue1) models.

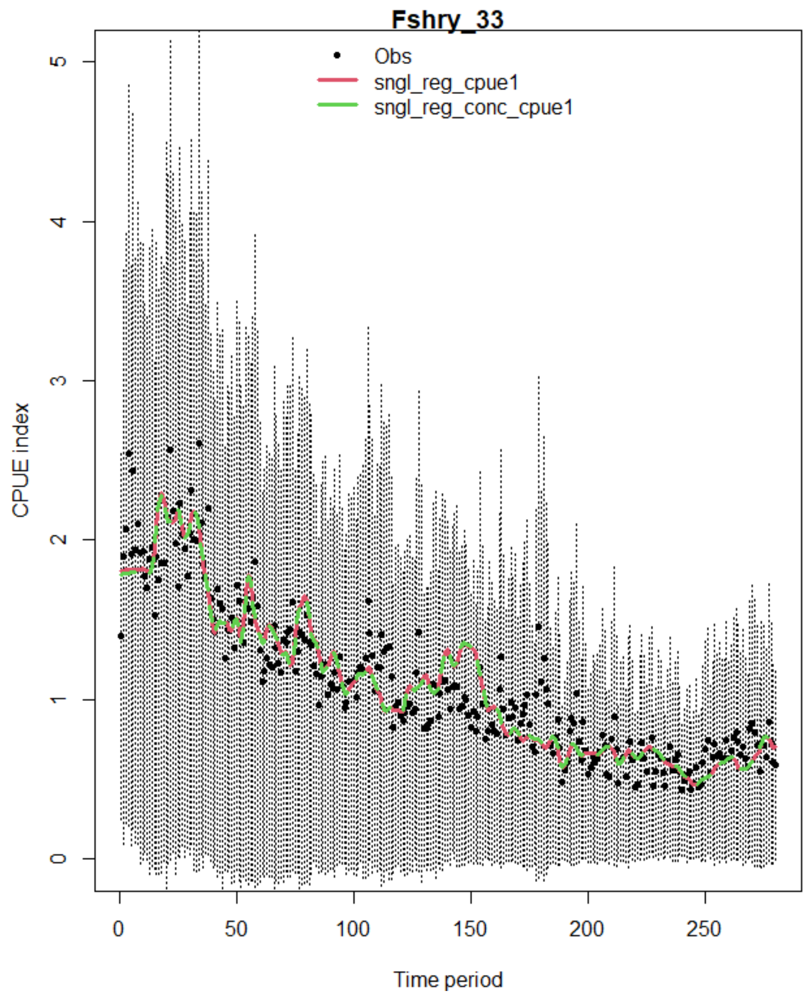
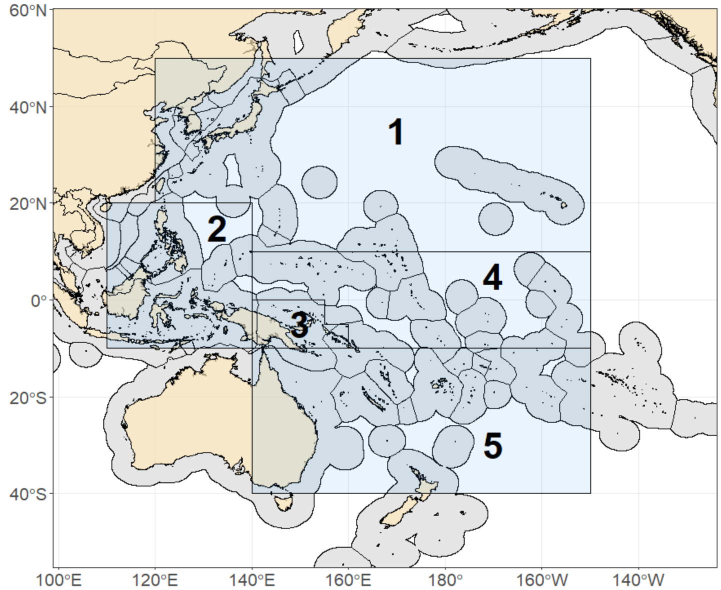


Figure A.9. Comparison of the fit to the observed CPUE indices between the single-region models employing the non-concentrated (sngl_reg_cpue1), and concentrated (sngl_reg_conc_cpue1) likelihood formulations. Vertical dashed lines are the index + or - CV.



The geographical area covered by the stock assessment and the boundaries of the model regions for the 5 region structure that was used for 2023 WCPO yellowfin tuna assessment.