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Updates on the 2019 SEAPODYM Review
(WCPFC Project: 62)

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SPC OFP[1]

[1] Oceanic Fisheries Programme of the Pacific Community

Executive Summary

WCPFC21 tasked the SSP with providing an update to SC21 on its progress in addressing issues raised by the 2019 SEAPODYM review (WCPFC21 summary report, para 465). This paper provides the OFP team's response to the most recent SEAPODYM review (Dunn & Webber, 2019). It describes main achievements and progress in improving the SEAPODYM modelling framework following the reviewers' recommendations. SPC considers that the recommendations of the reviewers are fully addressed. Prior to describing how the reviewers' recommendations were addressed, we list major improvements to the model, its numerical code and analysis tools, which made a significant impact on the workflow and the current results:

1. Public code on GitHub with code documentation
2. New model reference manual
3. Data:
    a. Longline fisheries structure by unsupervised machine learning techniques
    b. Integration of early-life history data to inform model parameters:
        i. eggs hatching success as a result of laboratory studies;
        ii. larval density from broad scale larval surveys;
        iii. spawning seasonality from adult gonad sampling studies
4. Model structure:
    a. New observation model for early larvae density observed in larval net sampling
    b. Enabling alternative models for reproduction, accessibility to vertical layers, diffusion and mortality
5. Parameter estimation:
    a. Decrease of RAM needs by 55%
    b. Taylor derivative test
    c. Arbitrary number of forage groups in the estimation model
    d. Estimation of catchability trend parameter
    e. Stock likelihood term as a penalty function
6. R tools for model and estimation analyses:
    a. Libraries dym, seamaps, and seamove
    b. R codebase seapodym-reports.

Reviewer recommendations. *SEAPODYM has the potential provide a link between the targeted single species assessment models (e.g., MULTIFAN-CL) used to provide tactical management advice on key tuna stocks, and full simulation based ecosystem models (e.g., EwE) that allow understanding of the ecosystem relationships from climate change and fishing at a broad spatial and temporal scale. Consideration of how the advice from these different work streams can be more fully integrated would be beneficial and assist when developing the medium-long term research program for SEAPODYM. Clear identification of the research questions required by SPC and the role of the different tools available would be beneficial to informing future development.*

SPC response. SPC agrees with the reviewers that establishment of clear objectives for each modelling framework will assist in identifying development priorities for each approach. While each of the frameworks share or apply outputs from one another we do not agree that any are specifically designed to act as a link (or common thread) between them. SEAPODYM has been designed for the purposes of estimating the spatial dynamics in relation to environmental gradients to facilitate exploration of the response of stocks to different oceanographic regimes (e.g. ENSO, PDO cycles), consequences of spatial management and possible futures under differing climate change scenarios.

In this context the current broad development needs identified for SEAPODYM include:

- Code optimisation and parallelisation
- Inclusion of fishing and natural mortality estimation from conventional tagging data
- Modelling weight of fish
- Access to spawning location data (e.g. monitoring of spawning gonad or larval data)
- Standardisation of environmental forcings preparation pipelines
- Archival tag integration of vertical behaviour properties
- Evaluation of the loss in predictive power when downscaling

Reviewer recommendations. *While SEAPODYM provides an advanced and reasonably mature product suitable for generating advice, there are a number of key areas where research investment could be considered that would improve its usability and utility to SPC. Documentation of the underlying SEAPODYM software is available only as a draft document from 2009, and many of the model equations and assumptions are available only for specific aspects contained within a variety of reports, presentations, and published papers. Full documentation of the current code (and ongoing future modifications) would be most beneficial to allow transparency and collaboration on its development and provide assurance that the outputs represent best available science.*

SPC response. The model is now fully documented in the Reference Manual (2022), which is structured into four main chapters:

1) Fish Population Dynamics Model – Describes the underlying mathematical formulation and all parametric functions that link environmental variables to population dynamic rates.

2) Discretization and Numerical Solution – Details the numerical solver used to implement the model.

3) Configurations and Model Runs – Provides guidance for users on how to configure and execute the model software, including descriptions of input and output files.

4) Model Parametrization – Focuses on the parameter estimation approach and tools implemented within the SEAPODYM framework, including local and global sensitivity analyses, twin experiments, correlation and error analyses, and likelihood hypersurface projections.

The model code is currently publicly available for download and use. Besides the codebase, the GitHub repository https://github.com/PacificCommunity/seapodym-reports.git includes installation instructions, R tools to read input-output files, the Reference Manual, the example configurations, and code documentation generated by DOxygen software. The code allows generating five model instances: *seapodym* for simulation only, *seapodym_clte* for simulation and estimation, *seapodym_densities* to run the model of unexploited stock, *seapodym_habitats* to run the habitat models, and *seapodym_fluxes* to compute regional connectivity.

Since 2023 we have started the work on optimising the computer software with help of the scientific computing support team of New Zealand eScience Infrastructure. The report (Pletzer et al., 2023) on the code review and approaches for its parallelization can be seen in Code review for parallelization.

Reviewer recommendations. *SEAPODYM provides a valuable tool to inform and simulate data to validate the assumptions of management advice from the current assessment (MULTIFAN-CL) models for tunas. Additional model validation is required in order to verify that the equations and methods can replicate the standard fisheries models — specifically the population dynamics and broad scale movement. Simulation and validation of the SEAPODYM software would also be beneficial (using either MULTIFAN-CL and other spatially explicit models such as SPM or specific case models) to ensure the underlying population dynamics and movement assumptions are robust and consistent, where appropriate, with standard fisheries models used to provide management advice.*

SPC response. Species models developed within the SEAPODYM framework are systematically compared to outputs from stock assessment models, and any discrepancies are carefully investigated. As an example, one recent study helped to clarify the origin of a persistent positive trend in skipjack recruitment, which was estimated by MULTIFAN-CL in the earlier assessments but was not present in the SEAPODYM reference model being driven by environmental dynamics in the ocean forcing hindcast. The analysis revealed that the apparent increase in catch-per-unit-effort (CPUE) for Japanese pole-and-line fleets was not due to rising recruitment, but rather to *effort creep*—an emergent property captured by SEAPODYM.

Reviewer recommendations. *Consideration should also be given to the statistical implementation of the underlying estimation equations and assumptions. Specifically, the way in which input data are applied within the model (e.g., the use of kernel smoothed tag recapture data as an input) and the statistical assumptions (e.g., likelihoods) are implemented. Verification of these aspects would not be time consuming and would provide the basis for confirming the best use of input observations and validate that the underlying statistical aspects were consistent with other fisheries assessment practise.*

SPC response. The codebase currently supports multiple types of likelihood functions, including concentrated, normal, robustified normal, log-normal, Poisson, truncated Poisson, negative binomial, and zero-inflated negative binomial. For length frequency data, we consistently use the robustified normal likelihood, which was adopted from MULTIFAN-CL. However, for catch data by fishery and tag recapture distributions, users are free to test and select the likelihood function that best fits their data.

A Gaussian kernel transformation is applied specifically to the observed tag recapture distributions to account for uncertainty in the tag positions, and it was shown (Senina et al., 2020, 2025) that it is suitable for fitting the tag recapture data and estimating the movement parameters which are valid for predicting independent tagging data. Looking ahead, we may consider allowing modellers to parameterize these kernels directly via the parameter file.

Reviewer recommendations. *Spatial models, with large numbers of spatial and temporal observations are difficult to validate against statistical assumptions, simply as the dimensionality of observations results in large quantities of model diagnostics and fits that are difficult to distil into easily interpretable but informative summaries. Consideration should be given to further developing the standard model diagnostics, including visual representations of fits, and potentially replicating summaries typically seen with standard fisheries assessment modelling output. Additional development on the SEAPODYM model diagnostics, including reproduction of standard fisheries assessment diagnostics would be beneficial in demonstrating model adequacy, and to highlight those conclusions where spatially explicit models result in alternative predictions of tuna species stock dynamics and status.*

SPC response. The R codebase *seapodym-reports* is under active development by the SPC team and is hosted in a private (SPC-shared) GitHub repository: https://github.com/PacificCommunity/seapodym-reports.git. It provides tools for analyzing model outputs from both simulations and optimizations.

Three types of reports are currently supported—*optimization* reports, *validation* reports, and full species reports, which includes all types of graphics and summaries to be used in scientific reports or peer-reviewed publications. These reports include various diagnostics such as convergence indicators, summary tables, visualizations of model structure, quantifications of fishing impact and population depletion over time and by age, fit metrics for each data type, global and regional time series, spatial distribution maps, and comparisons with other models—either alternative SEAPODYM configurations or parameterizations, or estimates from MULTIFAN-CL

Reviewer recommendations*. As a means of developing the validation and model diagnostics, a key initial test case might be to reproduce a standard fishery model in SEAPODYM where the movement and functional relationships to underlying forage fish and environmental dynamics have been 'turned off'. Comparison of the model likelihoods, fits, and parameter estimates would then confirm that the underlying processes and statistical equations were correct. Then, iteratively add to this model the specific spatial and environmental functional relationships back, developing an 'audit trail' (also known as a bridging analysis') that demonstrates the effect of additional complexity in movement and population productivity assumptions on the model outputs and management conclusions that could be drawn.*

SPC response. Turning off the environmental dynamics in SEAPODYM effectively disables the spatial dynamics and associated reproduction processes, as these are defined in terms of environmental drivers. This leaves only the temporal and age dimensions, resulting in a pointwise model that must be fitted to aggregated time series data. Performing such an exercise with the existing SEAPODYM codebase would be impractical. Instead, a simplified version of this model could be more easily implemented in R or using the TMB (Template Model Builder) package. However, we do not expect such a simplified model to yield a good fit to the data.

Conversely, the full SEAPODYM model is continually evolving and improving as it is applied to different species and new data types are integrated to inform model processes. Today, we can integrate geo-referenced catch, length frequencies, conventional tagging data and scientific data on early life stages dynamics from larval samples and laboratory experiments. Indeed, only the underlying advection-diffusion-reaction equations with age structure are always retained, but the higher-level model structure, involving the definitions of each of three modelled processes - reproduction, movement and mortality- is not fixed; it can be adapted by modellers to incorporate processes that are essential for the biology of the target species. For example, in the case of temperate albacore tuna, it is necessary to account for seasonal migrations to spawning sites. Each application—whether involving a new species, novel data sources, different ocean forcing, or a different ocean basin—challenges the model structure.

Through ongoing work on parameter observability, inter-parameter correlations, optimization, and fit validation using both MLE data and fully independent datasets, the most appropriate model structure is established for each species-specific reference model, given the current SEAPODYM version and available data.

We agree with the reviewers that documenting the "audit trail" for each reference model will facilitate repeatability and aid interpretation and review by end-users and other developers.

Reviewer recommendations. *As SEAPODYM provides a well-advanced research tool for the investigation of spatially driven fish dynamics, the requirement for additional research in this area will likely increase in the future. Currently, additional research questions that may use SEAPODYM are limited by a small number of individuals who can access or run the program. Considerations should be given to expanding the user base of SEAPODYM, potentially by making the underlying program more available and developing interfaces or tools to allow the investigation of alternative model structures, assumptions, and observational data in an efficient manner; and improving the ability to allow for sensitivity analyses of alternative climate change scenarios and operational fishing scenarios (including total removals, fleet distribution and fleet catch ratios between fleets).*

SPC response. Thanks to the establishment of a public GitHub repository for SEAPODYM codebase, allowing version control and sharing, our current membership includes:

- SPC, NESI, MOi, IRD, CLS, CSIRO, IEO, IATTC, Utrecht University, University of New Caledonia

A cross-platform software specifically designed at SPC to visualize SEAPODYM inputs and outputs, is now also on GitHub https://github.com/PacificCommunity/ofp-fema-seapodyview/releases/tag/v4.0-alpha-124

An open-source repository has been established for climate projections – https://osf.io/qa8w4/

- Note the external access to these data (Amon et al., 2023; Mouillot et al., 2023).

The web platform provides infographics of the climate change projections for tunas https://ofp-sam.shinyapps.io/ofp-FEMA-climate-dashboard

A web-interface demonstrator for the fishing mortality evaluation during the climate change, in the framework of the EU NECTON Project

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