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ONGOING DEVELOPMENT OF THE SPATIOTEMPORAL TAGGING MODEL

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SUMMARY

In a collaborative project between IATTC and DTU Aqua, a spatiotemporal tagging model was developed to estimate movement rates (SAC-13-08) and length-based natural and fishing mortality rates (SAC-14 INF-E) using the matrix exponential approach or the classic Kalman filter. Building on these movement estimates, a second spatiotemporal model was designed to estimate total biomass using a Petersen-type framework (SAC-15 INF-G). These models were applied to skipjack tuna in the Eastern Pacific Ocean (EPO), providing meaningful estimates of both relative and absolute biomass, which were subsequently incorporated into a benchmark stock assessment (SAC-15-04 REV). Ongoing development of the spatiotemporal tagging model aims to enhance usability, flexibility, and analytical capabilities. Key advancements include the development of a user-friendly and well-documented software package to facilitate its application to other fish stocks, the incorporation of formal residual estimation and diagnostic tests to improve model validation, and the inclusion of time-varying and length-specific habitat preference functions to better capture environmental influences on movement. These improvements will further refine stock assessments and support more robust fisheries management strategies.

1. INTRODUCTION

Historically, assessing skipjack tuna (SKJ, *Katsuwonus pelamis*) in Eastern Pacific Ocean (EPO) has been problematic due to the lack of a reliable index of relative abundance, the possibility of a dome-shape selectivity, and the lack of age-composition data, challenging its sustainable management. A state-space spatiotemporal model was developed to estimate movement rates, mortality rates, and biomass based on tagging data (conventional and/or archival tags) (SAC-13-08, SAC-14 INF-E, SAC-15 INF-G). The model describes movement based on the advection-diffusion equation and uses habitat preference functions to inform advection and diffusion rates. The habitat preference functions are smooth functions of environmental fields (e.g. sea surface temperature) (Thorson et al. 2021). The model allows estimation of separate parameters for active advection (taxis), informed by the gradient of any number of environmental fields, and passive advection (advection), informed by rate fields. While sea surface temperature was estimated to be an important predictor of the habitat preference and taxis component for SKJ in the EPO, ocean currents was estimated to be important for the passive advection component (SAC-13-08, SAC-14 INF-E). A combination of sea surface temperature and the kinetic energy of the water, which is calculated based on the ocean currents, resulted in the most robust results with both or any of the two tagging data types over a wide range of tested scenarios (SAC-15 INF-G). Two approaches can be used to estimate parameters: the matrix exponential or classic Kalman filter. The incorporation of spatial effort information into the model enables the estimation of spatially varying recapture probabilities, as well as length-dependent natural and fishing mortality rates. While the use of effort data influences the estimated habitat preferences and movement rates (SAC-14 INF-E), the manner in which effort is included appears to have limited impact on the overall movement estimates (SAC-15 INF-G). In particular, informing the model only about areas with (E > 0) and without effort (E = 0) - i.e., assuming a uniform distribution within fished areas - produced results similar to those based on alternative assumptions, such as effort scaled proportionally to fishing mortality or modeled using smooth functions. This suggests that movement estimates are more sensitive to the spatial presence or absence of effort than to its precise statistical distribution or magnitude. Estimated mortality rates for SKJ were in line with reported values (SAC-14 INF-E).

Building on the movement (and mortality) estimates, a second state-space spatiotemporal model was developed to estimate total biomass using a Petersen-type approach. The integration of these methods provided meaningful estimates of both relative and absolute biomass. For SKJ in the EPO, absolute biomass estimates between 2000 and 2023 ranged from 290 thousand to 3.6 million tons, with the highest concentrations found at varying longitudes around the equator (SAC-15 INF-G). Most estimates were characterised by high uncertainty, which was strongly correlated with the number of recaptures. However, estimates in five quarters had acceptable uncertainty levels (0.3 < CV < 0.6) and were relatively robust to a range of model assumptions. Sensitivity analyses indicated that biomass estimates were influenced by assumptions about natural and tagging-related mortality, as well as immediate and continuous shedding and non-reporting probabilities. Including effort information in the biomass estimation reduced uncertainty, but absolute biomass estimates then depended on the assumed relationship between effort and fishing mortality. Nevertheless, the relative temporal trends in biomass were consistent regardless of the assumed or estimated relationship between effort and fishing mortality.

Both absolute and relative biomass estimates were subsequently incorporated into the benchmark stock assessment for skipjack tuna (SAC-15-04 REV). This represents a significant advancement in the use of tagging data for stock assessment, as it provides a more comprehensive understanding of spatial dynamics and population structure. Ongoing developments of the spatiotemporal tagging model aim to further improve its applicability, accuracy, and flexibility in stock assessments and are presented in more detail below.

Here we describe the improvements including 1) creating a user-friendly R package, 2) residual and diagnostics, and 3) time-varying length-specific habitat preferences.

2. METHODOLODGY

One key objective in the development of the spatiotemporal tagging model is the development of a well-documented and user-friendly R software package (R Core Team, 2020) that will facilitate the model's application to a wider range of fish stocks, broadening its impact across different fisheries. While previous implementations of the tagging model were implemented in TMB (Kristensen et al., 2016), the software package is implemented in RTMB (Kristensen, 2024). The R package includes vignettes and detailed documentation, helping users to apply the tagging model to their specific data. The package is hosted on GitHub and allows users to report issues and contribute to the package development.

An important feature of a robust modeling toolbox are formal residuals and diagnostics tests, ensuring that uncertainties in movement and mortality estimates are better understood and accounted for. For example, residuals for the recapture location for conventional and archival tags using the Kalman filter can be estimated by:

$$\epsilon^{\mathrm{kf}} = (\epsilon_x, \epsilon_y) = \left(\frac{x_{t_c} - \hat{x}_{t_c}}{\sqrt{2\boldsymbol{D}^*(\psi_{t_c}, t_c)\Delta t \boldsymbol{I}_{2\mathrm{x}2}}}, \frac{y_{t_c} - \hat{y}_{t_c}}{\sqrt{2\boldsymbol{D}^*(\psi_{t_c}, t_c)\Delta t \boldsymbol{I}_{2\mathrm{x}2}}} \right)$$

Where epsilon is the recapture position residuals, x_{t_c} is the observed *x* location of a tag, $\hat{x}_{t_c}$ is predicted x location of a tag, y_{t_c} is the observed y location of a tag, $\hat{y}_{t_c}$ is the predicted y location of a tag, ***D**** is the diffusion rate, and ***I*** is the identity matrix. Estimated residuals in terms of x and y positions then be investigated as a function of the recovery time, their position and in terms of the distributional assumptions (Figure 1).

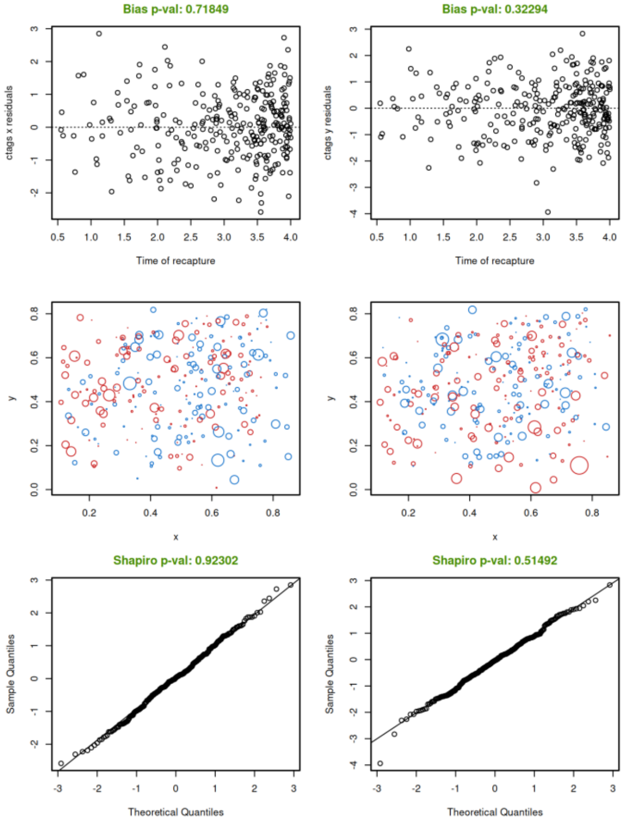

FIGURE 1. Example x and y residuals for Kalman filter for simulated data when the correct environmental fields are provided to the estimation model.

FIGURA 1. Ejemplo de residuales *x* y *y* para el filtro de Kalman para datos simulados cuando se proporcionan los campos ambientales correctos al modelo de estimación.

The figure shows the recapture position residuals regarding x and y coordinates (two columns) against time of recapture (first row), in space (second row), where the size of the circles indicates the absolute value of the residuals and the colour indicates whether the residuals are positive (blue) or negative (red), as well as QQ-plots (third row). For the first simulated example in which the correct environmental fields are provided to the estimation model, the residuals do not indicate any significant patterns (Figure 1). However, providing wrong environmental fields (such as only y coordinates) to the estimation model based on data that was simulated by use of more complex environmental fields leads to biased residuals that are not normally distributed and shows spatial patterns in the residuals, especially regarding the x coordinates (Figure 2).

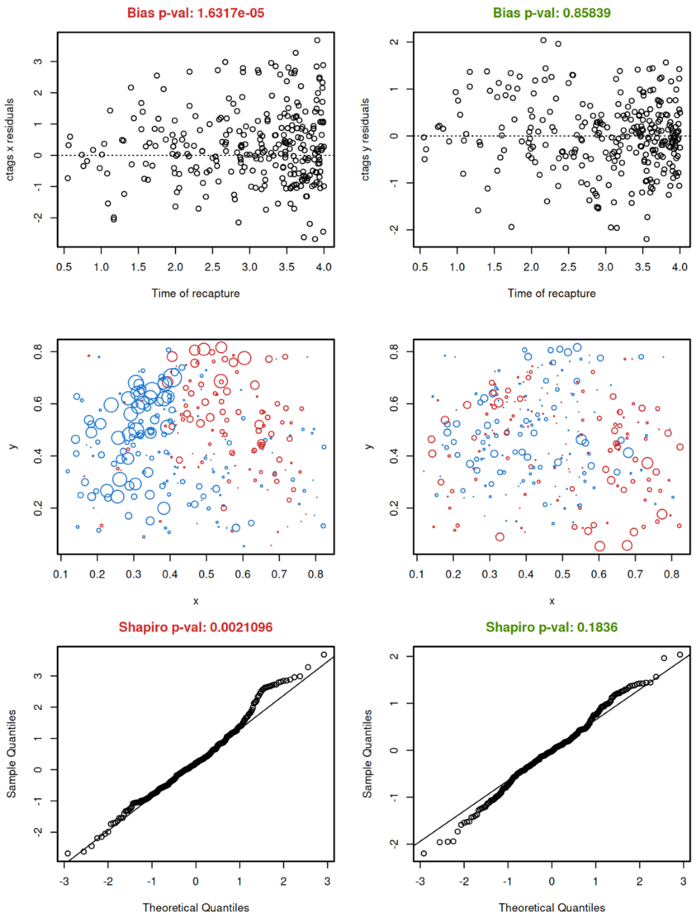

FIGURE 2. Example x and y residuals for Kalman filter for simulated data when a wrong environmental field is provided to the estimation model.
FIGURA 2. Ejemplo de residuales *x* y *y* para el filtro de Kalman para datos simulados cuando se proporcionan los campos ambientales incorrectos al modelo de estimación.

The inclusion of time-varying and length-specific habitat preference functions is another crucial step, as it allows for a more ecologically realistic representation of fish behavior, capturing how environmental conditions and ontogenetic changes influence movement and distribution patterns. Previously, the models assumed that habitat preference functions—defining movement as a smooth response to environmental fields—were constant over time (both within and between years) and identical across age or length classes. However, in reality, preferences for environmental features such as temperature or depth (e.g., coastal vs. offshore areas) are likely to vary seasonally and differ between life stages. These preferences may be linked to spawning migrations, thermal tolerance, or habitat use associated with maturity. To better capture this ecological complexity, the model framework has been extended to allow the estimation of seasonally varying habitat preference functions.

3. CONCLUSION

The development of the spatiotemporal tagging model marks a significant advancement in fisheries science, particularly for the assessment of highly mobile species such as skipjack tuna in the Eastern Pacific Ocean. By integrating movement dynamics, natural and fishing mortality rates, and total biomass estimation using innovative modeling approaches, this framework provides a comprehensive and data-driven method for improving stock assessments. The ability to estimate movement rates using the matrix exponential approach or the Kalman filter, combined with a Petersen-type model for biomass estimation, represents a major step forward in utilizing tagging data for robust stock assessments. The incorporation of these results into benchmark stock assessments underscores the practical relevance and credibility of the model in real-world fisheries management applications. The collaboration between IATTC and DTU Aqua has initiated this ongoing work, that has inspired other regions to start similar projects for the analysis and incorporation of available tagging data. Together, the advancements presented here will ensure that the tagging model continues to evolve as a powerful tool for fisheries science, improving the precision of stock assessments and informing sustainable fisheries management in a rapidly changing ocean environment. As fisheries management increasingly relies on data-driven approaches to ensure the sustainability of marine resources, this model provides an essential step forward in incorporating underutilized tagging data into fisheries modeling and management.

4. ACKNOWLEDGMENTS

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