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The development of spatio-temporal models of fishery catch-per-unit-effort data to derive indices of relative abundance

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ABSTRACT

Spatio-temporal models are increasingly used to develop indices of population abundance from fishery-dependent and –independent data. Developments in spatio-temporal index standardization were discussed at a workshop hosted by The Center for the Advancement of Population Assessment Methodology (CAPAM) titled "*Development and application of spatio-temporal models to derive indices of relative abundance*" (La Jolla, CA, USA; Feb. 26-March 2, 2018). This special issue includes ten submissions that highlight potential benefits arising from spatio-temporal index standardization including: (1) improved prediction for areas with little-to-no data; (2) capacity to weight densities by area to account for sampling rates that vary spatially; (3) calculation of the composition (e.g. age or length) of the indices and to weight predictions by catch to inform the composition of fishery removals, (4) estimation of distribution shifts and range expansion/contraction; and (5) capacity to combine data sources. The articles in this Special Issue highlight the need for continued development and testing for spatio-temporal index standardization methods, so that the relative strengths and weaknesses of different approaches are fully understood. The articles also identify topics that warrant further research including improved model diagnostics, accounting for biased rates of sampling ("preferential sampling"), and improvements in computational efficiency.

1. Introduction

Recent advances in spatial statistics, computational methods, and fisheries management have led to a rapid growth in the use of spatio-temporal models for index standardization. Although there is no recent summary regarding the use of model-based index standardization across model and software implementations, information is available for the use of one widely-used implementation involving the Vector Autoregressive Spatio-temporal (VAST) model (Thorson and Barnett, 2017). Spatio-temporal modelling based on VAST was used for index standardization in seventeen stock assessments from 2015 to 2018 (Thorson, 2019), and an additional eleven stock assessments in 2019 (Adams et al., 2019; da Silva et al., 2019; Ducharme-Barth et al., 2019; Gertseva et al., 2019; Haltuch et al., 2019; Ianelli et al., 2019; ICES, 2019; Taylor et al., 2019; Thompson and Thorson, 2019; Wetzel, 2019; Winker et al., 2019). The increasing use of spatio-temporal models for index standardization combined with the motivation to better model spatial dynamics of abundant cohorts of Pacific bluefin tuna as they moved through the fishery (Maunder et al., 2017) led The Center for the Advancement of Population Assessment Methodology (CAPAM) to host a workshop titled "*Development and application of spatio-temporal models to derive indices of relative abundance*" in La Jolla, CA from Feb. 26-March 2, 2018. Articles in this special issue (Table 1) are representative of discussions occurring at that workshop, and highlight five advantages to using a spatio-temporal model to standardize data:

(1) improved prediction for areas with little-to-no data;
(2) capacity to weight densities by area;
(3) capacity to estimate age/length composition and to weight predictions by fishery catch to inform the composition of fishery removals;
(4) estimation of distribution shifts and range expansion/contraction; and
(5) capacity to combine data sources.

We discuss each in detail below, and conclude by recommending topics for future research.

2. Benefit #1: improved prediction for areas with little-to-no data

Spatio-temporal models share information across space and time and can therefore fill in spatial cells that lack data and augment cells with low sample size. This can be viewed as an extension of post-stratification. Hashimoto et al. (2019) demonstrated the potential benefits of post-stratifying results from a survey for Pacific chub mackerel *Scomber japonicus* in the Northwest Pacific. By defining spatial strata that minimize within-stratum variance, post-stratification can improve precision and decrease standard errors when applying the stratified-random estimator for abundance (Cochran, 1977 pg. 134). Hashimoto et al. (2019) contributed to a growing literature on methods that automatically identify geographic boundaries to use during post-stratification of survey results, and showed that post-stratification resulted in better retrospective agreement between resulting indices and the results of a Virtual Population Analysis model than either nominal indices, or abundance indices produced using a generalized additive model (GAM).

Grüss et al. (2019) extended this argument by exploring the

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Table 1
List of papers in the special issue, including the software used for analysis, the type of data (either fishery-dependent catch-per-unit-effort or fishery-independent samples) and the region studied.

Paper	Software	Data type	Region
Currie et al. (2019)	VAST	Fishery independent	Benguela Current
Grüss et al. (2019)	VAST; GAM	Fishery-dependent	North and Central Atlantic
Gwinn et al. (2019)	Custom	Fishery independent	South Atlantic Bight
Kai (2019)	VAST	Fishery-dependent	North Pacific
Maunder et al., 2020	VAST	Fishery-dependent	Central Pacific
Murphy (2020)	INLA	Fishery independent	North Pacific
Hashimoto et al. (2019)	Custom	Fishery independent	North Pacific
Perretti and Thorson (2019)	VAST	Fishery independent	Northwest Atlantic
Thorson (2019)	VAST	Fishery independent	North Pacific; California Current
Xu et al. (2019)	VAST	Fishery-dependent	Central Pacific

potential benefits of replacing the stratified-random estimator with a spatio-temporal model. They use a simulation experiment to show that a spatio-temporal model minimizes residual variance by estimating the spatial scale over which density predictions should be "shrunk" towards data collected at nearby or geographically distant locations. In particular, Grüss et al. (2019) compared a stratified delta-generalized linear model (delta-GLM) with a delta-generalized linear mixed model (delta-GLMM), a spatio-temporal delta-GLMM, and a GAM. This comparison showed that the spatio-temporal delta-GLMM and the GAM outperformed stratified-random estimators. Similarly, Xu et al. (2019) and Maunder et al., 2020 argued that shrinking density predictions towards nearby data is especially important for analysis of fishery-dependent data, where the spatial footprint of the data may differ from the spatial scale of the stock assessment using the estimated abundance indices. Thorson (2019) discussed the potential benefits of using covariates to separately estimate variation in density and gear performance, and also to improve predictions either outside a modelled area (extrapolation) or at a finer spatial scale than the resolution of samples (interpolation). Finally, Thorson (2019) and Xu et al. (2019) discussed the potential benefits of estimating spatio-temporal variation that is correlated across time to improve predictions within areas that are sampled in some, but not all, years.

3. Benefit #2: capacity to weight densities by area

Thorson (2019) included a broad overview of the VAST package in R (Thorson and Barnett, 2017), and described fifteen decisions that must be made when standardizing abundance indices. These include defining the spatial domain over which densities are predicted and then summed when calculating an area-weighted abundance index. Thorson (2019) recommended using the spatial domain for the stock, ecosystem, or habitat assessment for which the output of a spatio-temporal model is being used. In cases where data are available only for a subset of this spatial domain, "area-weighting" then has the natural property that the resulting index has higher variance for years that sample a smaller proportion of the total area (variance of estimates increase by distance from the data). Similarly, Grüss et al. (2019) demonstrated the benefits of area-weighting by showing that alternative approaches (weighting each stratum equally, or defining the index for only a single stratum) resulted in biased abundance indices.

4. Benefit #3: capacity to estimate age/length composition and to weight predictions by fishery catch to inform the composition of fishery removals

One of the motivating factors of the workshop was to address the change in size of individual bluefin tuna *Thunnus thynnus* as they migrated through the longline fisheries (Maunder et al., 2017). This requires adding a fourth dimension (age or size) to the spatio-temporal model for this stock (Maunder et al., 2020). Other dimensions could also be added based on individual characteristics such as sex, maturity status, or life stage (Murphy, 2020; Perretti and Thorson, 2019). Maunder et al., 2020 introduced a novel alternative to "area-weighting" when calculating abundance indices by proposing to use "catch-weighting" where the predicted density at each location is weighted by the fishery catch at that same location to calculate an unbiased estimate of fishery removals for various size, length, age, and sex categories. Maunder et al., 2020 demonstrated that catch- and area-weighting produce different proportion-at-length estimates for yellowfin tuna *Thunnus albacares* in the eastern Pacific Ocean. They argue that the composition used in stock assessment models associated with the index of abundance should be based on area-weighted densities while that associated with the removals should be based on catch. The call for alternative methods for weighting predictions when summing across space has already been extended to include other cases, e.g., "predator expanded stomach contents" (PESC) weights stomach-content estimates by samples of predator biomass when calculating diet proportions over a fixed spatial domain (Grüss et al., 2020).

5. Benefit #4: estimation of distribution shifts and range expansion/contraction

Many papers highlighted the potential for spatio-temporal and generalized additive models to help understand spatial dynamics of stocks in ways that can also inform the structure of stock-assessment models. This supports previous research showing that spatio-temporal models can mitigate biases arising from changes in sampling design when analyzing spatial shifts (Thorson et al., 2016). For example, Currie et al. (2019) assembled estimates of distribution shifts and range expansion/contraction across species in South Africa. They then combined these estimates using a meta-analytic model to identify a westward shift and shrinking spatial extent for this assemblage on average. Similarly, Murphy (2020) estimated interannual variation in distribution for juvenile, adult male, and adult female individuals of snow crab *Chionoecetes opilio* and Tanner crab *C. bairdi* in the eastern Bering Sea; this analysis indicated different responses between species and size-classes to ocean warming, as well as potential changes in species overlap.

Kai (2019) used spatio-temporal index standardization models to show that declines in blue shark *Prionace glauca* abundance were concurrent with declines in the northern portion of their range, while subsequent increases were strongest in this northern portion. This paper highlighted the potential for spatial hotspots to inform the structure of stock-assessment models, e.g., where fisheries operating in different locations will likely have different patterns in catchability and selectivity. Thorson (2019) demonstrated the potential to forecast future distribution shifts using autoregressive spatio-temporal models; in this case-study, the magnitude of localized "density dependence" was used to forecast future apportionment across different management areas in the California Current. Finally, Perretti and Thorson (2019) described a northward shift for juvenile and adult summer flounder *Paralichthys dentatus*, and showed that this shift was not attributable to the set of commonly used covariates that were available in that region.

6. Benefit #5: capacity to combine data sources

Two papers showed that spatio-temporal models can be used to integrate data from multiple survey designs or gear types. Gwinn et al. (2019) combined data from chevron traps and video cameras mounted on the same gear for vermilion snapper *Rhomboplites aurorubens*. The video camera allowed the authors to distinguish the effect of local environmental conditions on gear performance (i.e., local catchability) for the chevron trap; this method could presumably be applied to paired sampling from other gears to unconfound environmental drivers of catchability vs. population density. Similarly, Perretti and Thorson (2019) demonstrated how to integrate bottom-trawl samples from offshore and nearshore sampling programs in the northwest Atlantic. These surveys sampled different, non-overlapping areas, but Perretti and Thorson (2019) estimated the ratio of gear performance between gears using a “regression discontinuity design” (Imbens and Lemieux, 2008) where nearby (but not paired) samples from the two gears were used to inform the expected ratio of catches that would occur if the two gears were deployed at the same place and time. The paper highlighted the potential benefits of combining the two surveys to achieve the spatial coverage that is also assumed in many stock assessments in that region.

7. Next frontiers for spatio-temporal index standardization models

In addition to compiling the benefits of using spatio-temporal models for index standardization demonstrated by the papers in this special issue, we compile research recommendations that would improve interpretation of future studies:

1 *Improved diagnostics for model adequacy and selection*: Thorson (2019) noted that there are model selection tools that are appropriate for existing spatio-temporal models. However, there is little research showing how to identify whether a spatio-temporal model has too poor of fit to be useful for index standardization (or any other purpose). Tests of model adequacy (“goodness-of-fit”) remain an important research topic in hierarchical models (Thygesen et al., 2017), and we encourage development of generic and automated procedures to adapt these methods for spatio-temporal models.

2 *Performance comparison across models*: Age-structured assessment models have undergone decades of performance comparisons, including designs where data are simulated and provided to analysts in a blinded experiment. However, spatio-temporal models have been developed more recently and consequently have had less performance comparison among model structures. Grüss et al. (2019) and Hashimoto et al. (2019) conducted simulation experiments comparing VAST, GAM, and area-weighted GLM and GLMMs, but there are few other examples of such comparisons from which to draw general guidance. We recommend routine testing of alternative spatially stratified and spatio-temporal index standardization models, to identify which features are likely to perform well or poorly given plausible forms of model mis-specification.

3 *Guidelines for model structure and interpretation given spatially unbalanced sampling*: Xu et al. (2019), Murphy (2020) and Gwinn et al. (2019) all predicted densities across a fixed spatial domain using spatially unbalanced data (i.e., where the spatial footprint varies among years); this illustrates that spatio-temporal models are already being used to predict densities in areas that have data in some but not all years. However, there is little guidance regarding circumstances when missing data can be accurately predicted using existing spatio-temporal models, vs. circumstances where results are likely to be misleading. Similarly, we recommend more research regarding how covariates or changes in model structure could mitigate problems arising from unsampled areas.

4 *Use of indices from spatio-temporal models in stock assessment models*: The standard approach of including indices in stock assessment models ignores any correlations among years. Output from spatio-temporal models includes the variance-covariance of the index and this could be input into the assessment model if available. However, few, if any, stock assessments allow for multivariate likelihood functions for index data (although see Ianelli et al., 2019). Integration of the index gets more complicated when composition data for the index and the catch are also estimated using a spatio-temporal model (Maunder et al., 2020). Appropriate multivariate likelihoods should be developed and implemented in general stock assessment packages.

5 *Computational efficiency*. Many of the applications made simplifying assumptions to reduce the runtime or ensure convergence. Characteristics that increase computational demands include fine spatial and temporal scales, number of knots used to represent spatial densities, and additional dimensions (Thorson, 2019). More work is needed to make spatio-temporal models computationally efficient to expand their application and increase their spatial resolution.

6 *Preferential sampling*. Finally, and possibly most importantly, fishery-dependent data are not random and results will be biased by preferential sampling (Conn et al., 2017). Grüss et al. (2019) explored biased sampling and showed that it substantially increased bias and imprecision relative to random sampling. Further research should determine when results will be biased by the preferential sampling due to fishers targeting areas with high catch rates and/or low by-catch rates, and how these biases can be minimized (e.g., using appropriate covariates).

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