Proceedings of the Technical Expertise in Stock Assessment (TESA) National Workshop on 'Methods for incorporating ecosystem information into single-species stock assessment models', 24-27 November 2025, St. John's, NL

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TABLE OF CONTENTS

ABSTRACT

Wheeland, L., Benoît, H.P., Edwards, A.M., Mazur, M.D., Regular, P.M., Robertson, M.D., Wor, C., Holt, C.A., Burton, M.A., Rideout, R.M., Neville, V.K., Boudreau, S.A., Varkey, D., Tai, T.C., Forrest, R.E., and Koen-Alonso, M. 2026. Proceedings of the Technical Expertise in Stock Assessment (TESA) National Workshop on 'Methods for incorporating ecosystem information into single-species stock assessment models', 24-27 November 2025, St. John's, NL. Can. Tech. Rep. Fish. Aquat. Sci. 3798: vi + 56 p. https://doi.org/10.60825/23sh-rq62

The Technical Expertise in Stock Assessment (TESA) group of Fisheries and Oceans Canada (DFO) held a national workshop on 'Methods for incorporating ecosystem information into single-species stock assessment models', in St. John's, Newfoundland and Labrador (NL) from November 24th to 27th, 2025. The workshop was chaired by Laura Wheeland (DFO NL Region), Hugues Benoît (DFO Quebec Region) and Andrew Edwards (DFO Pacific Region). It was attended by 29 DFO participants and three external participants from Norway, the United States and Memorial University of NL. The first day and a half were devoted to talks by participants, with 13 contributed by DFO scientists and three keynote seminars by the invited external experts. The talks were broadcast nationally by videoconferencing, with keynote seminars constituting part of a 2025-2026 national seminar series on an ecosystem approach to fisheries management. A plenary session during the afternoon of the second day centered around three topics: 1) general considerations for integrating environmental variables (EV) into stock assessments, 2) the advantages and challenges of using surplus production models to incorporate EVs in assessments, and 3) environmental effects on stock structure and assessment.

The last two days of the workshop were spent in break-out sessions followed by a plenary wrap-up session. There were four concurrent, break-out sessions that respectively discussed i) approaches for accounting for time-varying natural mortality in assessments and science-based advice, ii) incorporating qualitative ecosystem information into stock assessment models, iii) approaches for considering the spatial scale of environmental drivers when including those drivers in assessments, and iv) the use of DFO's high power computing (HPC) resources for simulations involving the incorporation of environmental considerations in assessments, science advice and management strategies. The first three break-out groups each produced a framework or guidelines to help structure and guide future work on the incorporation of environmental considerations in assessment models, while the fourth focused on accessing and using HPC resources. Overall, discussions highlighted ways EVs are already included in stock assessment, and both opportunities and challenges around advancing their incorporation in models and advice. The breadth and depth of discussions, the high degree of engagement by participants during the plenary and breakout sessions, and the identification of highly relevant and largely unresolved topics demonstrated the value of such an in-person workshop in fostering DFO's implementation of an Ecosystem Approach to Fisheries Management (EAFM). Work to include EVs in stock assessment, and the development of EAFM is a collaborative, iterative process. Participants recommended topics for future workshops, including: communicating risk-based EV-informed science advice; gaining and incorporating into assessments a more mechanistic understanding of EV effects, notably using causal models; and, practical considerations in including EVs in assessment models including bias-variance trade-off (when and how much to include), confounding effects on different modelled processes, and how they might affect reference points.

RÉSUMÉ

Wheeland, L., Benoît, H.P., Edwards, A.M., Mazur, M.D., Regular, P.M., Robertson, M.D., Wor, C., Holt, C.A., Burton, M.A., Rideout, R.M., Neville, V.K., Boudreau, S.A., Varkey, D., Tai, T.C., Forrest, R.E., and Koen-Alonso, M. 2026. Proceedings of the Technical Expertise in Stock Assessment (TESA) National Workshop on 'Methods for incorporating ecosystem information into single-species stock assessment models', 24-27 November 2025, St. John's, NL. Can. Tech. Rep. Fish. Aquat. Sci. 3798: vi + 56 p. https://doi.org/10.60825/23sh-rq62

Le groupe Expertise technique en évaluation des stocks (ETÉS) de Pêches et Océans Canada (MPO) a tenu un atelier national sur les « Méthodes d'intégration de l'information écosystémique dans les modèles d'évaluation des stocks mono-spécifiques », à St. John's (Terre-Neuve-et-Labrador) du 24 au 27 novembre 2025. L'atelier était présidé par Laura Wheeland (MPO, région de Terre-Neuve-et-Labrador), Hugues Benoît (MPO, région du Québec) et Andrew Edwards (MPO, région du Pacifique). Vingt-neuf participants du MPO et trois participants externes de Norvège, des États-Unis et de l'Université Memorial de Terre-Neuve-et-Labrador y ont assisté. La première journée et demie a été consacrée aux présentations des participants, dont treize par des scientifiques du MPO et trois séminaires principaux présentés par les experts externes invités. Les présentations ont été diffusées à l'échelle nationale par vidéoconférence, et les séminaires principaux s'inscrivaient dans le cadre d'une série de séminaires nationaux 2025-2026 sur une approche écosystémique de la gestion des pêches. Une séance plénière durant l'après-midi du deuxième jour s'est concentrée sur trois sujets : 1) les considérations générales pour l'intégration des variables environnementales (VE) dans les évaluations des stocks, 2) les avantages et les défis de l'utilisation de modèles de production excédentaire pour intégrer les VE dans les évaluations, et 3) les effets environnementaux sur la structure et l'évaluation des stocks.

Les deux derniers jours de l'atelier ont été consacrés à des séances de travail en petits groupes, suivies d'une séance plénière de synthèse. Quatre séances de travail simultanées ont porté respectivement sur : i) les méthodes pour tenir compte de la mortalité naturelle variable dans le temps dans les évaluations et les avis scientifiques; ii) l'intégration des informations qualitatives sur les écosystèmes dans les modèles d'évaluation des stocks; iii) les méthodes pour considérer l'échelle spatiale des facteurs environnementaux lors de leur intégration dans les évaluations; et iv) l'utilisation des ressources informatiques de calcul haute performance (CHP) du MPO pour les simulations intégrant des considérations environnementales dans les évaluations, les avis scientifiques et les stratégies de gestion. Les trois premiers groupes de travail ont chacun élaboré un cadre ou des lignes directrices pour structurer et orienter les travaux futurs sur l'intégration des considérations environnementales dans les modèles d'évaluation, tandis que le quatrième s'est concentré sur l'accès aux ressources CHP et leur utilisation. Dans l'ensemble, les discussions ont mis en lumière les façons dont les VE sont déjà intégrées à l'évaluation des stocks, ainsi que les possibilités et les défis liés à l'amélioration de leur intégration dans les modèles et les avis. L'ampleur et la profondeur des discussions, le haut degré d'engagement des participants lors des séances plénières et des séances de travail, ainsi que l'identification de sujets très pertinents et en grande partie non résolus ont démontré la valeur d'un tel atelier en présentiel pour favoriser la mise en œuvre par le MPO d'une approche écosystémique de la gestion des pêches (AEGP). L'intégration des VE dans l'évaluation des stocks et le développement de l'AEGP constituent un processus collaboratif et itératif. Les participants ont recommandé des sujets pour les ateliers futurs, notamment : la communication de conseils scientifiques fondés sur les risques et tenant compte des VE; l'acquisition et

l’intégration dans les évaluations d’une compréhension plus mécaniste des effets des VE, notamment au moyen de modèles causaux; et les considérations pratiques liées à l’intégration des VE dans les modèles d’évaluation, y compris le compromis biais-variance (quand et dans quelle mesure les inclure), les effets confondants sur les différents processus modélisés et leur incidence potentielle sur les points de référence.

1. INTRODUCTION

Fisheries and Oceans Canada (DFO) continues to move towards an Ecosystem Approach to Fisheries Management (EAFM). DFO's national EAFM working group has recently wrapped up an important phase of more concerted EAFM implementation nationally. This phase involved the completion of over 30 case studies across Canada and the production of four key products to further implementation of EAFM. The first, termed the *Gap Analysis*, undertook detailed accounting of the integration of environmental variables (EVs) in fishery stock assessments in Canada. The study concluded that as of 2021, 102 stock assessments (48 %) made use of EVs, and that an additional 65 % of the remaining 110 stocks could make use of EVs in the future, conditional on resources (Kulka et al. 2022). Furthermore, current approaches used in the assessment of Canadian fish stocks were found to constitute an *ad hoc* collection of methods and procedures. The second product, termed the *Case Study Synthesis*, is an in-depth review of 31 DFO case studies to better understand how ecosystem knowledge has been applied in the science-management cycle and to identify opportunities/challenges to greater integration of EVs in fisheries decision-making (Pepin et al. 2023). The third product, termed the *Fishery Management - Science EAFM Feedback Tool*, is an internal DFO communication procedure to structure collaboration between DFO's Fishery Management and Science sectors for implementing EAFM throughout the fisheries management cycle, emphasizing cross-sectoral feedback on ecosystem considerations at each step in the process. Finally, the fourth key product, termed the *EAFM Methods Toolbox*, is an indexed and searchable database of methods and approaches for the provision of ecosystem-informed science advice (Cogliati et al. 2025). The *Toolbox* outlines factors to consider when selecting a method, such as data availability, resource requirements (e.g., staff, expertise, time), and types of advice required, and provides guidance on the most appropriate method(s) for a given situation. An accompanying user's guide provides brief descriptions for several methods organized into eight general classes, providing relevant links or references (Cogliati et al. 2025).

The recent publication of the *EAFM Methods Toolbox* was a key motivating factor for DFO's National Workshop on 'Methods for incorporating ecosystem information into single-species stock assessment models', which took place on 24-27 November 2025, at DFO`s Northwest Atlantic Fisheries Science Centre in St. John's, NL. The general intention for the workshop was to share practical technical knowledge from across DFO regions, and external sources, on methods included in the *Toolbox*, and to identify and advance other methods and approaches that should be included in the future, while building capacity within DFO. Another key objective for the in-person workshop was to facilitate the development of collaborations for the application and development of new methods and approaches.

The workshop was developed and hosted by DFO's national committee on Technical Expertise in Stock Assessment (TESA), which has had a mandate since 2009 to provide training within DFO and to hold workshops that have direct relevance to DFO's capacity to conduct stock assessments. The current workshop was intended – in part – to build on the outcomes of a successful and similarly themed TESA workshop that took place in Nanaimo, BC, in November 2016, titled 'Incorporating an ecosystem approach into single-species stock assessments' (Edwards et al. 2017). Although naturally complimentary, these workshops were distinct in scope and application. Considerable recent advances in the number, diversity and sophistication of methods for EAFM and in single-species assessment modelling internationally and within DFO were also important motivators for the present workshop.

Twenty-nine scientists from DFO and three invited experts from Norway, the United States and Memorial University of Newfoundland participated in the workshop (Figure 1; Appendix A. Workshop agenda and list of participants). The first day and a half were largely devoted to talks by participants, with 13 contributed talks by DFO scientists and three keynote seminars by the invited external experts. The remainder of the workshop involved a mix of break-out group and plenary discussion sessions. The agenda for the workshop and the list of participants is provided in Appendix A. Workshop agenda and list of participants. This document summarises the talks and discussions to document current thinking and motivate future work.

Figure 1. Group picture of the TESA workshop participants (missing Divya Varkey, Hannah Munro). Photo: Jenna Makrides

2. CONTRIBUTED TALKS AND INVITED SEMINARS (DAYS 1 AND 2)

The mornings of the first and second days of the workshop were devoted to contributed talks by DFO Scientists from across Canada. There were 13 contributed talks, covering diverse topics ranging from addressing time-varying demographic processes, to approaches for identifying and including EVs in assessments (Appendix B). The contributed talks were broadcast nationally within DFO via MS Teams.

The three invited external participants presented keynote seminars during the afternoon of the first day. These seminars were broadcast nationally, within DFO and to external partners via Zoom as part of the 2025-2026 Stéphane Plourde Memorial National Ecosystem Approach to Fisheries Management seminar series. There were close to 180 online participants during the keynote seminars, in addition to the workshop attendees.

In his presentation, Daniel Howell noted that ecosystem-based fisheries management (EBFM) has advanced considerably in Europe and the USA based on recent published reviews and his recent involvement in workshops and assessment meetings. A major scientific challenge remains the shift from simple, time-varying data inputs to the complex, mechanistic inclusion of multiple, non-independent environmental covariates. Daniel underlined that EBFM is fundamentally more than advanced stock assessments, also encompassing aspects such as spatial management and the effective communication of complex advice. While Science can provide the “least worst” models to better inform management actions, it cannot deliver exact or precise outcomes of ecosystem management, nor can it choose between competing priorities.

Matthew Robertson drew from his own research to argue that, although a variety of approaches now exist to incorporate ecological variation in stock assessments, determining the appropriate level of complexity and understanding the consequences of modelling assumptions remain key challenges. For instance, incorrect assumptions about which demographic processes are affected by specific environmental change can have important impacts on model reliability and especially the inferences that are drawn. He underscored the value of evaluating a range of models of increasing complexity and the need to regularly re-evaluate assumptions.

Steve Cadrin presented a multistep process implemented in New England stock assessments in response to a degradation in assessment reliability and management effectiveness resulting notably from rapid ocean warming. The process involves first reviewing information on ecological interactions and anticipated environmental effects, then testing relationships between environmental indices and population processes (e.g., distribution, recruitment, growth, or maturity), followed by developing stock assessment models including environmental covariates. New England Yellowtail flounder stocks were presented as a case study for this type of approach. In common with the other two keynote speakers, Steve argued for iterative advancement of EAFM.

Abstracts for the contributed talks and invited seminars are provided in Appendix B.

3. PLENARY DISCUSSION (DAY 2)

Plenary discussions led by the workshop co-chairs took place during the afternoon of days 2 and 4 of the workshop. The plenary during the second day was a divergence from the proposed agenda to capitalize on the expertise of external participants and continue discussion on items identified during the contributed talks. Day 2 plenary discussion covered three topics: 1) general considerations for integrating environmental variables into stock assessments, 2) the advantages and challenges of using surplus production models to incorporate EVs in assessments, and 3) environmental effects on stock structure and assessment. A summary of each of these topics is presented in the following subsections.

3.1 GENERAL DISCUSSION ON INTEGRATING ENVIRONMENTAL VARIABLES INTO STOCK ASSESSMENTS

The discussion emphasized the tension between achieving ecological realism and the necessity of moving forward with pragmatic, "good-enough" models. There was consensus that this should follow an iterative and stepwise process, starting with research to identify relevant environmental attributes and their relationship with assessment processes before implementing them in models. A key challenge is determining the “least-worst” approach for integration, acknowledging that "best-available science" might not always be immediately achievable. Historically, non-EV approaches worked well when the environment was more stationary and fishing was the main driver of population dynamics. With environmental change, there is often a need to include EVs in models to have acceptable model performance/reliability. Crises such as population collapse can be strong motivators for investigating EV effects. However, rather than being reactive, assessments should proactively look at EVs, potentially starting with simple surplus production approaches or models to explore the relationship between catch and productivity across species, especially when data are limited. However, given shifting priorities, advice timelines, and available resources, this is not always possible. Two of the experts noted that limitations in the inclusion of EVs often do not stem from a lack of information, but from e.g. ineffective communication of science advice, or a lack of management's capacity or willingness to consider EVs.

For some stocks, a robust (well-tested) Harvest Control Rule might suffice to promote sustainable management under changing ecosystem conditions, but only if the underlying reference points are suitable, which increasingly may depend on the ecosystem state. While random effects can be used to model time-varying processes in assessment models, adding covariates to models can help fill in missing data in hindcasts and enhance understanding, even though they may not always improve model suitability. Participants noted that covariate-informed projections may be more accurate, but they are often less precise (greater uncertainty incorporated in estimates). Key steps in incorporating EVs include using a thought experiment, identifying key hypotheses, checking if data informs the conceptual model, deciding how to model the EV, and then communicating the resulting risk-based advice.

Ecosystem summaries, as planned for DFO’s implementation of EAFM, were identified as a valuable vehicle for examining emerging signals and potential relationships. This information provides context for the assessments but may also motivate formal inclusion of EVs in models.

Participants underlined the importance of stakeholder engagement, notably with Indigenous partners, in the scoping and development of new approaches, and in working towards approaches that incorporate or account for socio-economic objectives and local knowledge systems.

3.2 ADVANTAGES AND CHALLENGES OF USING SURPLUS PRODUCTION MODELS TO INCORPORATE EVS IN ASSESSMENTS

Steve Cadrin led a discussion which he began by arguing that surplus-production models offer a valuable, less mechanistically precise approach to fisheries assessment, particularly when exploring the effects of the EVs on population dynamics. The motivation for using these types of models is that they require less detailed biological information, making them applicable to data-limited stocks. Rather than trying to evaluate environmental effects on individual biological processes in a model from the start, it may be simpler to focus on the higher-level property of production, which inherently integrates growth, survival, and recruitment. Production is defined as $P_t = B_{t+1} - B_t + Y_t$, where B_t is biomass and Y_t is yield or catch, all at time t. Production can be modelled as a function of EV covariates, and evidence of possible relationships, combined with knowledge on mechanisms, can motivate follow-up investigation of effects on surplus production model growth rate and carrying-capacity parameters. However, analysts must also consider possible EV effects on the observation portion of production models, notably, via effects on survey catchability. Furthermore, predation could be added as an explicit removal, like catch; however, one needs to ensure that the scale and selectivity of the predation and the fishery removals are the same.

A key advantage of production models is that they are useful for both data-limited situations and for exploring drivers and connections in data-rich stocks that use more complex models. The challenge lies in identifying the relevant environmental connections, which are species- and system-dependent. In cases where the environment affects time-varying productivity it is acknowledged that correctly specifying lags in environmental variables is a challenge and will be imperfect. It was also noted that when processes are cohort- or age-based, for example, and data are available to inform at this level, simplifying to a production model has little value beyond exploratory work. Overall, it was emphasized that the criteria used to incorporate EVs should not be stricter than those applied to select what fishery and survey data are used in population models.

A participant proposed that the application of tools like Empirical Dynamic Modeling (EDM) to assessment residuals and detect unmodeled processes or patterns in lag space. This would provide a check on whether observed variability is truly random or indicative of an unaccounted-for process.

Figure 2. Invited expert Dr. Steve Cadrin leads a discussion on consideration of surplus production models in the context of environmental effects.

3.3 ENVIRONMENTAL EFFECTS ON STOCK STRUCTURE AND ASSESSMENT

Building on Steve Cadrin's considerable experience with issues concerning stock structure and the consequences of misalignment between the biological, assessment, and management definitions of stock, the group discussed the importance of considering environmental effects on stock structure within the context of fisheries management and assessment. Environmental changes, such as range expansion and shifting distribution, can invalidate the core assumptions defining a stock. If the stock identification is wrong, attempts to quantify other population processes may be fundamentally flawed. Steve argued that every stock assessment should proactively address stock identification, incorporating the latest data (e.g. tagging, genetic, otolith) to check consistency with current boundaries. Such changes have cascading effects on key assessment components, including the catchability of surveys and fisheries, perception of food web dynamics, and natural mortality. The stock assessment process is therefore seen as a vital opportunity to flag and describe these changes, proposing necessary framework adjustments or benchmarks.

While science-driven adjustments to assessment areas are possible, changes to formal management divisions can be nebulous and complex. The discussion drew a parallel between the non-stationarity of population processes and the non-stationarity of stock structure, arguing that both need similar considerations. A major practical challenge is the impact of changing distributions on the appropriateness of surveys in providing comparable indices of abundance and biomass. Changing established survey designs and stratification can be difficult and have multiple consequences. Accounting for distribution shifts by modelling time-varying catchability can increase the risk of misattributing the change to other population processes, such as natural mortality. The discussion concluded noting a dilemma: "Stocks moving out of your survey is terrible," and "Changing your survey is terrible"—forcing scientists to choose the "least worst" option to maintain the integrity of the data and resulting advice. What this “least worst” looks like will be stock and area specific.

4. BREAK-OUT GROUPS (DAY 3, 4)

Four potential break-out group topics were identified by participants prior to the workshop. A brief description of these topics, with the name of the associated leader is available in Appendix C. There was discussion of potential additional break-out group topics, but participants were keen to dig deeply into the original ones, and no new specific topics were identified during a short plenary discussion. As some of the breakout groups ran for multiple days while others were shorter, some participants moved between multiple groups.

The sub-section that follows includes summaries of the break-out group discussions as reported by each group, noting that in some cases these discussions deviated from the original proposed topic, as was expected. Participants also moved between groups across days 3 and 4 as discussions naturally developed.

4.1 WHEN M ISN'T CONSTANT: ECOSYSTEM-DRIVEN MORTALITY AND ITS CONSEQUENCES FOR MANAGEMENT ADVICE.

Participants: Paul Regular, Mariano Koen-Alonso, Robyn Forrest, Andrew Edwards, Daniel Ricard, Hugues Benoît, François-Étienne Sylvain, Fatemeh Hatefi, Victoria Neville, Laura Wheeland

This breakout group took place across days 3 and 4. Led by Paul Regular, the group examined a case study on Northern Cod (*Gadus morhua* in NAFO Div. 2J3KL) and discussed best practices for exploring time-varying M more generally. On day 4 participants also explored an R tool being developed to aid in explorations of time-varying processes.

4.1.1 PART 1: Presentation by Paul Regular: Northern Cod Assessment

The Northern Cod assessment uses a state-space age-structured model (NCAM, Cadigan 2016a,b). It extends back to 1954, integrating juvenile surveys and fitting a stock-recruitment curve to enable productivity-linked reference points. Survival shifts were treated as hypotheses about natural mortality (M) rather than random noise, and covariates such as availability of prey-species Capelin (*Mallotus villosus*) were tested and eventually embedded in the NCAM formulation following a framework review meeting in 2023 (DFO 2024a, Regular et al. 2025a,b; Regular 2025). Time-varying estimates of fishing mortality (F) and M began in the assessment model in 1954 but were poorly informed in the early years, relying mainly on tagging data. Model inputs improved after 1962 with the addition of catch-at-age data, and further again after 1983 with the introduction of offshore trawl surveys. Abundance indices from the trawl surveys are produced using standard, reproducible stratified analyses. In contrast, catch-at-age inputs are manually constructed each year, and documentation of the decisions underlying these reconstructions is missing for most years. As a result, historic catch-at-age estimates are difficult to reproduce. This issue could be alleviated by following a well-documented and reproducible framework, such as the structured hierarchy of decisions to generate catch-at-age estimates implemented in the catchR R package developed in the Quebec Region (Ouellette-Plante et al. 2022), however issues with data structures and incomplete sampling challenge the broad application of such a package.

Baseline M Options: Three baseline options for M were considered in the model: i) constant age-invariant M; ii) Lorenzen allometric M (Lorenzen et al. 2022); and iii) regime-shift models. The constant age-invariant option was chosen due to insufficient data to reliably estimate allometric effects and the inability to predict regime shifts.

There has been considerable debate in the literature about the relative contributions of F and M to the collapse of this stock. For F to be the only cause, the unreported catches would have to have been massive, likely to exceed demand of black market cod. Still, unreported discarding was reported to have occurred due to flooded markets and undersized fish.

NCAM uses a censored catch likelihood approach, which gives the model the option to "choose" whether to associate losses to F or M. The model has the option to select higher F within pre-specified annual bounds that were co-developed with the fishing industry. Note that this approach is discussed further in section 4.1.2 with its application to Atlantic cod in NAFO

Subdivision 3Ps as an example of qualitative information being integrated into analysis by translating it into a statistical feature of model.

However, the behaviour of the censored catch approach continues to be questioned, especially how the model distinguishes between F and M. The model may simply smooth through the space, finding the "path of least resistance" in the likelihood. Simulation tests indicate that the approach may not reliably estimate the magnitude of catch underreporting.

Capelin-linked M: Capelin availability was hypothesized as a bottom-up driver of M, with low Capelin availability leading to starvation and higher mortality (Regular et al. 2022; 2025b). The covariate used was a ratio between Capelin and Cod biomass. Following the approach used in the Woods Hole Assessment Model (WHAM, Stock and Miller 2021), the Capelin:Cod ratio was smoothed using a random walk and changes in M were modeled as a function of the expected covariate value. Akaike information criterion (AIC) comparisons confirmed the covariate's relevance. Models with time-varying M but without Capelin still fit the data but lacked the ecological linkage to support forecasting.

Seal-linked M: Two formulations were explored to link Cod M with predation by Harp Seals (*Pagophilus groenlandicus*): i) a consumption model splitting total mortality into F + seal M + other M, using seal diet-based age shares with deviations following a two-dimensional first-order autocorrelation (2D AR(1)); and ii) an abundance covariate approach applying harp seal indices to age blocks. Signals were strongest on juvenile Cod, but effects were not retained due to data limitations and concerns about confounding effects. Seal diet data lacked temporal resolution, distinguishing Atlantic cod from Greenland cod (*G. ogac*) in stomach samples proved difficult, and there were concerns that hard-part analysis (i.e. otoliths) overrepresents small fish in the diet. Changes in groundfish composition and seal foraging behavior added uncertainty, making the approach impractical despite theoretical plausibility. Tests also showed that the model-estimated seal-linked M signal was correlated with the Newfoundland and Labrador Climate Index (NLCI), a composite index of physical environmental indicators that characterizes the state of the ocean climate at the Newfoundland and Labrador Bioregion scale. Since environmentally-driven M mechanisms have been considered in earlier versions of the NCAM model, and are also expected to act more strongly on small/young fish, the observed relationship between the estimated seal-linked M signal and the NLCI indicates that seal-linked M dynamics estimated by the model may be confounded with M associated with large-scale environmental conditions. It was concluded that the impact of seals and climate on Cod M requires further research to reliably discriminate between these two sources of mortality.

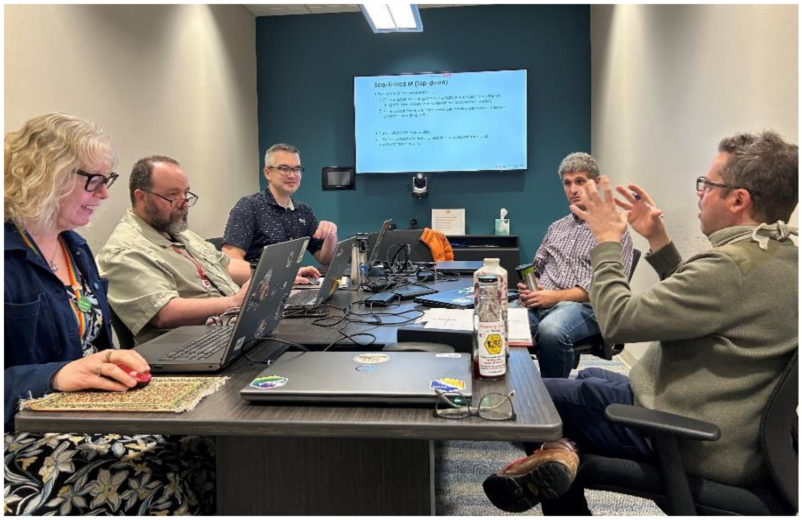

Figure 3. A subgroup engages in lively discussion around predation-linked estimation of natural mortality.

Implications for Advice: Incorporating data back to 1954 improved understanding of stock dynamics and enabled estimation of Beverton–Holt stock–recruit relationships. Revised Limit Reference Points (LRPs) were developed, shifting from a coarse proxy based on medium levels of recruitment to a long-term, productivity-linked metric, the biomass at the maximum sustainable yield (B_{MSY}). While stock size did not change appreciably with the new model, stock status was updated from the critical to the cautious zone of the Precautionary Approach (DFO 2009), due to the improved understanding of the long-term productivity of the stock. This change (spawning biomass remained the same but the perception of stock status improved) proved to be a challenge to communicate to managers, stakeholders, and the public at large, and required clear communication strategies.

Retrospective revisions of LRP and the connection with Capelin: The revised LRP was set at 40% of B_{MSY}, where B_{MSY} was calculated with the full time-series averages of M, stock-recruit relationships, and life-history parameters. Averaging non-stationary metrics has proven to be challenging as it results in retrospective revisions of the LRP, underscoring the need and possible avenues for future research on time-varying reference points. If M continues to increase, the B_{MSY}-based LRP will decrease, raising concerns about shifting thresholds for serious harm.

The LRP for Capelin in Div. 2J3KL was also discussed. Capelin itself is at very low biomass (but not below its LRP). The Capelin LRP is based on the Capelin acoustic biomass index as no estimate of absolute Capelin biomass exists for this stock, and it is set based on the assumed ecosystem need for Capelin: using Cod as a proxy indicator for ecosystem status, the Capelin LRP is defined as the equilibrium Capelin index level required to maintain Cod at its own LRP based on a bioenergetic-allometric model for Cod dynamics (Lewis et al. 2025). Capelin is still fished as a roe fishery, before spawning, with the expectation that most spawning Capelin will die after the fishery, as they only spawn once. As such, Capelin is difficult to manage. In any given year, the acoustic survey (~May) occurs after the capelin assessment meeting (~March), so its results are not available for the assessment until the next year. Although the trend in the acoustic survey is considered an acceptable indicator of the full Capelin stock trajectory, this survey does not cover the full population (i.e., there is a lack of an absolute estimate of population size). A suite of models is used as a forecast tool during the assessment for predicting the Capelin level expected in the upcoming acoustic survey (Lewis et al. 2019). These models include a range of ecosystem covariates, and at each assessment the best model from this suite is used to forecast the expected Capelin level. Work on reviewing and improving this forecast model suite, including the covariates being used and the hypotheses underlying them, is ongoing. Northern Cod and Capelin constitute two interconnected assessments, where ecosystem covariates are considered for both stocks.

Further Discussion: The estimation of time-varying M in an assessment model requires having data for at least one fishery independent survey that provides information on changes in total mortality (Z) over time. The group emphasized the need to first explore time-varying M without covariates, referencing examples from Pacific Herring (*Clupea pallasii*; DFO 2024b) and Northern Shrimp (*Pandalus borealis*; Johnson et al. in prep), where non-parametric approaches have been used to address unknown drivers or model deficiencies. The group noted that time-varying M in Atlantic Canadian stock assessments has been modelled in one of two general ways. For instance, models for Northern cod and Northern Gulf of St. Lawrence cod incorporate time-varying M as a stationary first order autoregressive process, correlated over ages and years. This approach estimates age and year deviations in M around age-specific long-term means. Projections of M from such a model revert rapidly to those means. In contrast, models for numerous groundfish and two herring stocks in the southern Gulf of St. Lawrence model M as a random walk for blocks of ages. Random walks are non-stationary processes in that the long-term average is not constant. Projections of M from these models constitute random changes from the terminal M estimate that do not revert to any long-term mean or initial values, although a drift parameter could be added to the random walk to project further trend in M values. Based on these considerations, the choice of approach might therefore be dictated by whether M is expected to vary about a mean or to display long term change. The choice has consequences for both projections and the estimation of reference points that clearly warrant further research.

The group noted that the state-space assessment model package “SAM” implements process error on cohort transitions rather than M. This approach can account for changes in M, as well as other factors that affect numbers at age such as migration (i.e., numbers at age in a cohort can increase over time). This approach is also optional in WHAM, as is time-varying M. The Canadian assessment for eastern Georges Bank cod, which is implemented in WHAM, assumes process error on cohort transitions because of evidence of migration in some years, but interprets the overwhelming decrease in process error deviate values over time as evidence of increasing M. Guidance on whether to model process error on cohort transitions or M would be beneficial.

For stocks displaying long-term cycles in biomass, density-dependent M can also be explored (e.g., Fournier 1983; Forrest et al. 2018; DFO 2025a). Other approaches for treating M in stock assessments are discussed in Johnson et al. (2014) and Punt et al. (2021).

4.1.2 PART II. Guidance for exploring and explaining variation in M

For decades, much of fisheries science has focused on recruitment–environment relationships as the primary pathway through which ecosystem variability and density-dependence influences population dynamics (see Haltuch et al. 2019). In contrast, relatively little attention has been directed toward understanding how the environment and ecosystem state shape survival, expressed in stock assessment models through natural mortality (M). Where M research does exist, it has historically emphasized top-down processes such as predation mortality (e.g., Doherty et al. 2025). Far less work has explored bottom-up drivers such as prey availability or oceanographic conditions, or proximate effects such as body condition (but see e.g., Dutil and Lambert 2000; Casini et al. 2016a; Boldt et al. 2021; 2025; Regular et al. 2022). As a result, bottom-up or environment-driven M remains an underdeveloped area within stock assessment modeling. This section provides a structured approach for practitioners to evaluate, model, and communicate time-varying M, helping to bridge this gap and support more ecologically informed assessments. The proposed approach was based on the experience and expertise of the group members during discussions and could certainly be expanded upon.

Preamble

The following applies when you have sufficient fishery-independent composition data (age and/or length) to track cohorts and infer total mortality. In surplus production or delay difference models, directly estimating time-varying M is likely to be impossible although estimating temporal variation in parameters that describe productivity more generally within these models has been done (e.g., Mildenberger et al. 2019).

Also note that here, M represents all sources of mortality other than reported fisheries removals (including estimates of discards), and “time-varying” refers to trends or regime shifts, not random fluctuations around an average level.

Step 0. Scoping stage

Begin by identifying which population and/or observation processes may be varying through time (e.g., catchability (q), M, F, recruitment, selectivity, immigration, emigration). Many of these processes can be confounded in assessment models, so it is essential to clarify which hypotheses are plausible and where trade-offs exist. For instance, if q and M are both time-varying, teasing them apart is likely an intractable problem without highly informative composition or tagging data. Ideally, one can assume survey q is time-invariant but there may be cases where this isn’t the case, e.g., when availability to gear is density-dependent (e.g. species like Redfish *Sebastes spp.* which occupy different parts of the water column depending on their density and size).

Regarding population processes, carefully consider the dominant process. Should process errors be on cohort-deviations (N-at-age in a state-space model) or M deviations? This is not entirely a statistical decision and can be informed by comparing model behaviour and diagnostics and/or previous knowledge regarding movement and survival. If you think M is the dominant process, estimate M deviations. If movement dynamics are thought to dominate interannual additions or subtractions, use cohort-deviations.

Time-varying processes in assessment models can be confounded, and attempting to include 'competing' processes can lead to a lack of model convergence or the production of non-sensical results. In addition to the confounding between M and q identified above, time-varying selectivity and cohort deviation are also likely to be confounded with changes in M. Furthermore, the specification of numerous time-varying processes can lead to better model fit at the expense of generality and predictive ability, following the classic trade-off between bias and variance. This further underscores the need to carefully consider which population or observation processes are likely to vary directionally over time.

The group discussions identified a number of notable articles that provide important background on state-space methods used to estimate time-varying parameters. Johnson et al. (2014) formulates an approach to the estimation of time-varying parameters, specifically M, and provides guidance on the use of state-space models while identifying potential pitfalls of these methods. Time-varying estimates are often used to identify regime shifts, and the article by Klaer et al. (2015) proposes a scoring methodology to identify regime shifts and highlights sources of confounding information. The population model developed by Cadigan (2016a) implemented time-varying natural mortality. Estimation problems encountered by state-space models are described by Auger-Méthé (2016). The implications of inappropriate values of M in stock assessments are discussed by Punt et al. (2021). Another approach that can accommodate time-varying parameter estimation was presented by Li et al. (2025) where random effects are applied to numbers-at-age transitions. The special issue of Fisheries Research on natural mortality (https://www.sciencedirect.com/special-issue/10NSQ74ZXD9) also contains a number of relevant articles.

Step 1. Establish whether M is likely trending through time

Use diagnostics and empirical evidence such as:

- Residual or retrospective patterns from existing assessment models, which respectively indicate a lack of model fit generally and likely misspecification of one or more key population or observation processes.
- Abrupt survival changes not explained by fishing; or evidence from estimating total mortality from data (e.g., catch curve analysis).
- Tagging or survey-based mortality estimates.
- Assess where time-varying processes are likely acting in the population – whether through cohort deviations, natural mortality, or shifts in selectivity – and prioritize which effects should be modelled as time-varying.
- Biological evidence, e.g., increased predators, decreased prey, abrupt changes in body condition.

Note that the existence of any of these types of evidence does not necessarily imply non-stationarity in M. For example, retrospective patterns can be caused by other processes (e.g., time-varying unreported catch, or time-varying selectivity).

Time-varying M is typically introduced only after multiple lines of evidence point toward non-stationary survival and other explanations have been ruled out. The strength of biological evidence for such changes is likely to vary across stocks.

Be cautious when adding time-varying M simply because modern tools make it technically feasible, but not necessarily appropriate and correct. Apparent changes in survival may instead reflect other time-varying processes, such as shifts in selectivity or catchability.

If there is no evidence for time-varying M: use constant M and document rationale.

If time varying M is evident: proceed to step 2.

Step 2. Identify the likely source(s) of variation

- Bottom-up: prey availability, energy limitation, evidence for prey limitation seen in body condition (e.g., Boldt et al. 2019, 2025; Regular et al. 2022).
- Top-down: predation pressure (e.g., Doherty et al. 2025)
- Environmental: temperature (could include heat stress), hypoxia (e.g., Casini et al. 2016b; Receveur 2022).
- Unaccounted-for catch: e.g., in Northern Gulf cod, the trends in M vary with Total allowable catch and F, which could be caused, for instance, by unreported commercial fisheries catches, depredation (fish removed from fishing gear by predators, sea lice) (Benoît et al. 2026). Catches in recreational fisheries lacking catch monitoring are another example. While it can be appropriate to implicitly include unaccounted-for catch in M, since it constitutes fishing mortality that is apparently not directly amenable to fishery management action, its inclusion is likely to hinder identification of drivers of natural mortality. Consequently, these catches should be dealt with separately from M if possible.
- Density-dependent M: e.g., Pacific herring (DFO 2025a).
- Unknown: unexplained survival anomalies

If the source is bottom-up, top-down, environmental, or unaccounted-for catch: use hypothesis-driven modelling.

If unknown: consider exclusively non-parametric M forms.

Step 3. Formulate and evaluate candidate hypotheses for time-varying M

Once the sources of variation for M have been identified, they need to be coded into the assessment model in ways that either represent clear hypotheses for those sources of variation, or explicitly recognize that the implementation constitutes the best we can do given the limitations imposed by the data available.

- H0: constant M (assumed or estimated)
    - It must be noted that it is often difficult to estimate even constant M given data constraints and confounding factors.
- H1: M regimes (step changes in M, defining blocks of constant Ms over time)
    - M regimes could be associated with ecosystem-level regime shifts, or other population and/or ecosystem processes that may impact the background productivity level of the stock. It may be important to consider lags in the system.

- While most ecological processes are not expected to produce sharp changes in M, apparent M regimes could represent an approximation for processes that we cannot model more precisely (Klaer et al. 2015; Wor et al. 2025).
  - The identification of the change point of a regime could be done as part of the estimation process, but are more commonly hardwired into the model based on expert elicitation or external analysis (e.g., Rodionov 2004). Either way, this represents a rather blunt instrument to represent changes in M that can be more nuanced in reality. Strong evidence for a regime shift may only become apparent many years after it started.
  - Consider whether the assumed regimes introduce a false sense of precision; variation explained by the break-points will not be carried forward in the projections. In the context of projections, consider if the step changes can be predictable.
- H2: allometric M
  - Likely to introduce a trade-off between survey catchability/selectivity and M.
  - May underestimate adult mortality (e.g., adult mortality for several Atlantic groundfish stocks are higher than expected under allometric M; e.g. Perreault and Cadigan 2021; Regular et al. 2025b).
- H3: smooth/stochastic M (RW, AR1, spline)
  - This choice impacts projections and reference points
  - A random walk (RW) assumes no reversion to a mean state; recent trends in M will persist and carry forward into projections.
  - A first-order autoregressive (AR1) process assumes partial reversion to the mean; deviations diminish over time as M drifts back toward its long-term mean. The rate at which M returns to the mean is a direct function of the strength of temporal autocorrelation.
  - A spline provides a smooth historical trajectory but has limited extrapolation capability. Without constraints, the fitted spline may exhibit edge effects, continuing in the direction of the final slope.
- H4: EV-linked M (environmental or ecological covariates)
  - Does the environmental variable (EV) time series overlap the modelled period?
  - Is the mechanism biologically credible and documented?
  - Are there lags or strong collinearity?
  - If data are insufficient: drop from the model and use available evidence to corroborate/validate trends outside the model implementation (e.g. correlation of the H3 M signal with H4 hypotheses).
- H5: Density-dependent M (compensatory and/or depensatory)
  - Carefully consider circularity in calculating equilibrium reference points (where M is a function of Biomass and vice versa; e.g., Forrest et al. 2018).
  - What is the evidence for density-dependent adult M (e.g., cyclic changes in abundance)? What is the hypothesized mechanism? Intraspecific interference within the functional response? Prey limitation? Intraspecific competition for habitat?
  - Keep in mind that density-dependent effects in common age-structured assessment models are usually limited to juvenile stages, modeled in the stock-recruit function, while standard stock production models (e.g. Schaeffer model)

include implicit density-dependence as a core process to regulate stock productivity.

Step 4. Fit Hypothesis Models

Implement candidate models representing each hypothesis that is considered relevant.

Ask whether remaining hypotheses are actually competing or simply choices that need to be made based on first principles or due to data limitations.

Step 5. Check Diagnostics

Assess:

- Retrospective patterns
- Residual diagnostics
- Patterns in process errors: are there unexplained temporal trends in the process errors? Do they match your assumptions?
    - Ultimately what we would like is a covariate that is a fixed effect which captures systematic trends in the population process.
- Do the results make sense? (e.g. are the catchability estimates so low that it makes the population so large that the fishery is irrelevant?).

Consider whether M is absorbing variation due to:

- Selectivity
- Catchability
- Recruitment
- Survey error
- Unaccounted-for catch

If checks fail: modify or reject the hypothesis.

Step 6. Compare models and select most appropriate

Comparing and selecting models is not an automatic process. Multiple dimensions need to be considered and weighed. These include assessing:

- Biological realism (i.e. which formulations are more broadly realistic for the system being modelled)
    - This is critical; a good statistical fit with a model that is biologically unrealistic is not a useful model, but a biologically realistic model with a bad fit is also of limited use. There is balance to be achieved that, at this stage of the process, is within the “art part” of the art of modelling.
    - Consider how the stock-results fit/don’t fit the ecosystem picture (e.g. ecosystem summary).
- Information criteria (AIC, WAIC)

- Be careful not to rely too much on information criteria for fitting stock assessment models.

- Forecast skill / hindcasts
  - If an EV is included, it is important to consider whether the covariate can be projected. How do we project EVs? Are projections available? If not, develop scenario-based advice. This could be with multiple sensitivity analyses, which are used to select a single “best” scenario for the advice (e.g. short-term state of covariate is low/medium/high), or as alternative operating models in management strategy evaluation (MSE), where alternative management procedures (MPs) are tested for robustness to uncertainty in environmental drivers.
  - For tactical projections, the EV may not improve forecast skill. It may be more informative for medium- to long-term projections.
  - Cross-validation type retrospective analyses are likely useful for evaluating forecast skill (Kempf et al. 2023). Further research could be conducted on the forecast skill of a model with and without an EV covariate. Inability to forecast the EV reliably may render the model no better than standard projections from the non-parametric model.

While the evaluation of these elements provides information for model-selection, ultimately there is always an expert judgement component to select a given model. Given all of the above, we need to decide if one or many of the plausible models under consideration can be deemed acceptable for its intended use. It is equally important to be explicit that, by accepting (a) given model(s) for some uses (e.g., short term projections), this does not automatically endorse the model for other uses (e.g., as an operating model within MSE). A model’s adequacy (or not) is always a function of its intended application.

If facing a difficult choice amongst plausible models, consider whether model averaging would be appropriate (it probably won’t be if models represent different structural assumptions).

If on an MSE path, consider using the most plausible alternative hypotheses as operating models (as part of a “reference” set of operating models; see Punt et al. 2016). It is also possible to include less plausible alternative hypotheses as part of an extra “robustness” set of operating models.

Step 7. Translate results into advice

The effective implementation of a model in a stock assessment context requires not only that the model be technically appropriate, but that we clearly communicate to decision-makers and stakeholders the implications of its results. In relation to time-varying M, it is important to clarify how this:

- Affects absolute SSB
- Affects estimated fishing mortality
- Impacts reference points (LRP, USR, RR) – while considering whether reference points should change if M is changing
  - This may require considering alternative types of reference points (e.g. should reference points based on historical average biomass or total mortality

(Z) be considered? Should ecosystem or multispecies reference points be considered?)
- Impacts on apparent stock status when reference points change
- Impacts on rebuilding trajectories
- Impacts on risk of biomass decline and uncertainty
    - For cases were EVs are used, this may require an explicit consideration and representation of the uncertainty of those EVs.

We should not lose sight of the fact that, while stock-assessment models are commonly used to inform short-term management decisions, we also need to consider medium and long-term impacts and factor these into the overall advice. Given the uncertainty that surrounds projections, only looking at short term horizons can obscure the detection of underlying trends that become more evident over longer time horizons.

Step 8. Communicate clearly and transparently

Prepare:

- Technical explanation for CSAS
- Plain-language summary for decision-makers and stakeholders
- Key caveats & assumptions. Focus only on critical ones; do not dilute the main message, burying it under a litany of potential pitfalls.
- Monitoring recommendations to validate proposed mechanisms/hypotheses.

4.1.3 PART III. Exploration of "tinyAM" tool

Following the discussion on processes for M explorations, the group explored tinyAM ("tiny assessment model"; a.k.a. TAM), which is an experimental R package under development for fitting age–structured stock assessment models using RTMB (Kristensen 2026). It is designed to be flexible, modular, and lightweight, making it easy to experiment with different model structures and process assumptions.

We focused on exploring various model fits to the built-in data on Northern cod, drawing on the expertise within the workshop participants to contribute to ongoing efforts to address research recommendations for the Northern cod assessment. While the package allows for quick changes to various structural assumptions regarding the population processes, further vetting and testing is required.

4.2 INCORPORATING QUALITATIVE ECOSYSTEM INFORMATION INTO STOCK ASSESSMENT MODELS.

Participants: Mackenzie Mazur, Catarina Wor, Carrie Holt, Aaron Adamack, Meghan Burton, Andrew Harbicht, Kevin Hedges, Rick Rideout, Xinhua Zhu, Daniel Howell, Victoria Neville, Laura Wheeland

This breakout group was held on Day 3, led by Mackenzie Mazur, and explored the application of qualitative information for incorporating ecosystem information and EVs into stock assessment models. Stock assessment scientists are accustomed to working with explicit objectives, quantitative data, and statistical models to deliver advice. They also often routinely encounter qualitative information pertaining to fish populations, such as details of the fishery and ecosystem conditions. Determining how to interpret and include this information presents an important challenge for stock assessment. Because qualitative information often emerges from different knowledge systems and may be expressed in non-quantitative ways, those trained primarily in stock assessment may perceive challenges related to its interpretation, documentation and use within assessment models. Differences in how qualitative and quantitative information are generated and interpreted can, in some cases, lead to different emphases or insights depending on the methods applied. For example, Lee and Lautenbach (2016) showed that the methods used to explore ecosystem relationships can influence which relationships are identified, underscoring the importance of interpreting qualitative and quantitative information together rather than in isolation.

One way in which qualitative information can meaningfully contribute to stock assessment processes is by helping to guide and interpret quantitative models and model outputs. This remains an important area of ongoing effort. Qualitative observations indicating that ecosystem changes may be occurring can inform how stock assessment models are developed, parameterized, and interpreted. For example, if knowledge holders such as fishers or other on-the-ground or generational experts report unusually low inshore catches, shifts in seasonal events (e.g. spawning), changes in habitat use, or increased predator presence, these observations can guide the development of model scenarios or highlight where scientific advice may carry additional uncertainty. In practice, this information can be incorporated through approaches such as sensitivity analyses or use of risk qualifiers. Sensitivity analyses involve exploring how assessment outcomes change under different plausible assumptions or scenarios, while risk qualifiers are used to explicitly communicate sources of uncertainty that are not fully captured within the assessment model. Incorporating qualitative information can improve understanding and strengthen advice and can be particularly valuable in data-limited situations where qualitative information may be more prevalent than quantitative data.

In many cases, qualitative ecosystem information may be considered in the early, formative stages but is omitted from the stock assessment model due to challenges associated with translating qualitative descriptors and categories like “warm weather” or “high water level” into rigorous and numerical values that can be used quantitatively, as e.g. statistical priors or inputs in assessment models. While it is possible to include information such as categorical data into assessment models, these methods are often not explored. Popular modeling platforms like Stan (Stan Development Team 2025) and TMB (Kristensen et al. 2016) do not easily handle categorical distributions (i.e. variables expressed as discrete states or classes), complicating the inclusion of qualitative states such as productivity regimes. Incorporating categorical variables is possible, however, with platforms like JAGS (Plummer 2003) and Nimble (NIMBLE Development Team 2024).

When evidence is provided by invited experts, the exclusion of such information from advice due to difficulties associated with e.g. interpretation or incorporation into assessment models can contribute to perceptions that these contributions are not being considered or respected, particularly when such evidence comes from experts who are also members of rights and/or stakeholder groups. It is therefore best practice to engage invited experts throughout the incorporation of this information into the assessment process. Where practical challenges make direct inclusion in stock assessment modelling infeasible, this stage of the process provides an appropriate opportunity for such information to be incorporated through contextual or interpretive text.

That said, when qualitative information is included solely in risk assessment or as supplementary contextual material, and is not directly embedded within model outputs, there is a risk that it may receive less prominence in the overall advice or subsequent decision making. Many decision-relevant outputs, such as limit reference points, stock status zones, and management triggers, are derived directly from stock assessment models. In instances where such integration is not feasible or does not directly improve model performance or understanding of quantitative data, qualitative information can still play an important role through complementary mechanisms. Furthermore, there may be opportunities to consider how management triggers or indicators could, where appropriate, also reflect qualitative measures alongside quantitative ones.

Within DFO assessment practice, qualitative information is increasingly recognized as valuable; however, its effective use often depends on the application of appropriate social science research methods. Best practices in social science include considerations around careful interview design, thoughtful sampling, informed consent, reflexivity, attention to context, and avoidance of leading questions. Most stock assessment scientists do not have formal training in these methods, which can lead to uncertainty or discomfort regarding how much weight to assign to qualitative information within a quantitative assessment context.

Although there are clear challenges associated with incorporating qualitative information into stock assessments, there are opportunities to do so at multiple stages throughout the assessment process (Figure 4), with multiple approaches for how/when this may occur in a single-species assessment model (*Figure 5*). Workshop discussions highlighted that qualitative information is already being incorporated, often implicitly, at various stages of the stock assessment process. Though the role of qualitative information may not be immediately apparent, nor explicitly documented, within assessment products. The objective here is to examine how qualitative information can contribute across different steps of the stock assessment process and where appropriate, to highlight examples from previous assessments. This exercise suggests that qualitative information may be playing a more substantial role in stock assessments than is currently recognized.

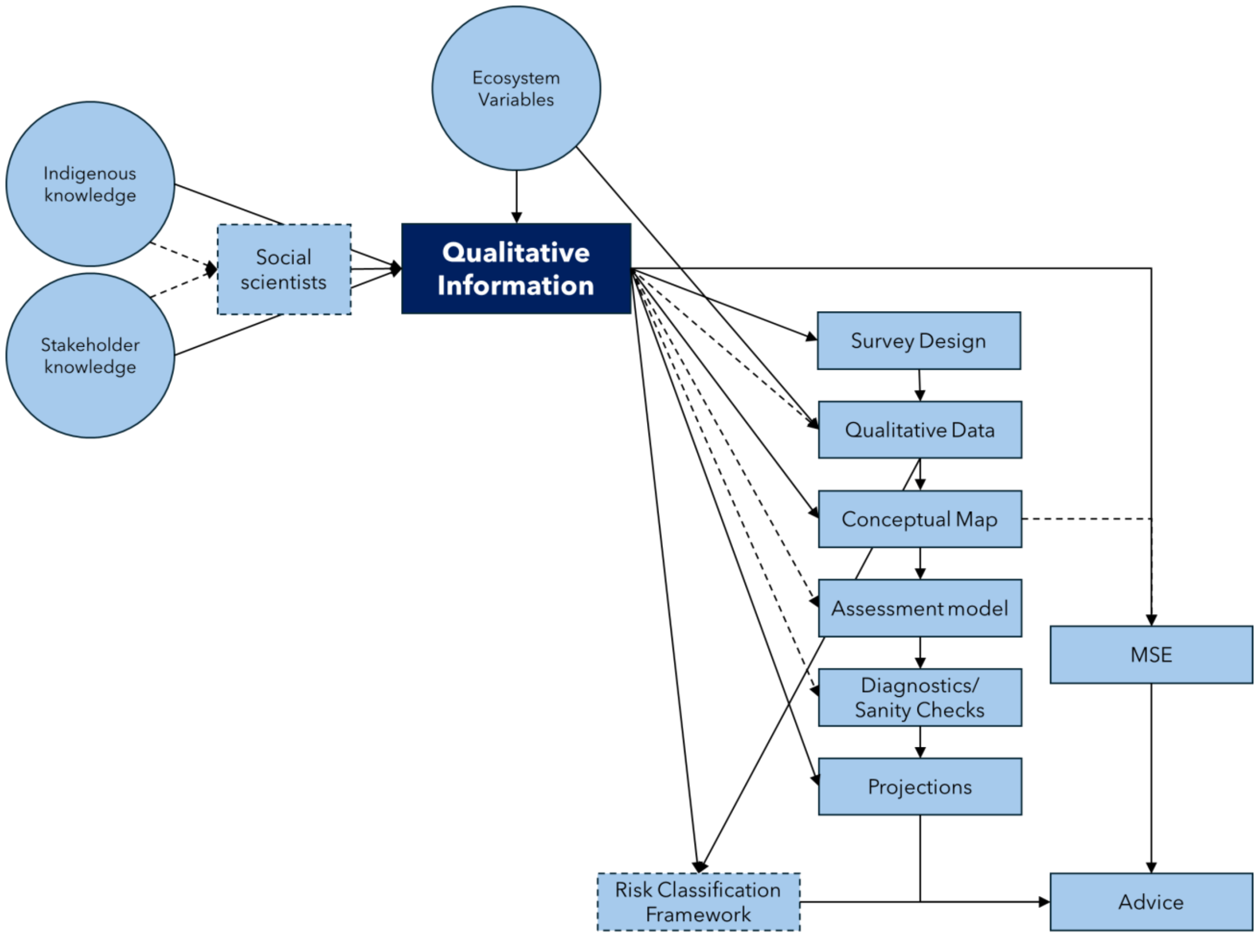

Figure 4. Conceptual diagram of how qualitative information can contribute to the single-species stock assessment process and management strategy evaluation. Each box is a practical component within the stock assessment process (e.g. knowledge or data source, analytical tool, advice output, etc.). Circles show inputs that contribute to the pool of qualitative information available for consideration that can then be translated into a stock assessment process. Dashed lines represent connections or components that may be available or possible, while solid lines show connections which can nearly always be made .

4.2.1 Qualitative Information in Survey Design

The first step of the assessment process that qualitative information can inform is in the survey design. Survey design is a vital step to ensure that data used in quantitative assessments are representative of the population/stock being assessed. Qualitative knowledge on factors like when and where a target species occurs, habitat distribution can inform the survey area and timing. This may be from fisher or Indigenous knowledge, expert opinion, or anecdotal reports, etc. Qualitative input can also inform potential gaps or biases in survey design over time. This may contribute to explorations of model parameters such as survey catchability estimation, inform assessment sources of uncertainty, or contribute to survey revisions or planning. Qualitative has been and is used to inform DFO survey design.

4.2.2 Qualitative Information as Quantitative Data

Qualitative information is often used to determine which sources of quantitative data are useful for a stock assessment. For example, some surveys are not designed to catch a given species and therefore may not represent that species' biomass trends, and that information should be taken into account in choosing data sources. Qualitative information can also be used to identify environmental and catchability covariates to use in index standardization models. For example, a group of Indigenous community members have been conducting a community-based monitoring program for Dolly Varden in the Rat River, Northwest Territories since 1996. When collecting catch per unit effort (CPUE) data for migrant fish, a group of environmental variables, like water level (low, normal, and high), debris content (few, some, and lot), and water color (clearing, clear, and dirty), have been recorded to track the seasonal upstream migration of mature fish using the community's traditional ecological knowledge (TEK). Daily observations of quantitative datasets based on TEK were downloaded from the national hydrology historical hydrometric portal (https://wateroffice.ec.gc.ca/mainmenu/historical_data_index_e.htm) to quantify the water level and discharge for CPUE standardization (Zhu et al. 2025). In this case, long-term Indigenous and community-based observational evidence informed quantitative analysis through its integration with hydrological data.

4.2.3 Application To Conceptual Maps

Qualitative information can be used to identify a list of environmental drivers and explore their relationships with population parameters relevant to the assessment. Then, a conceptual map identifying how key variables may interact to drive population dynamics can be developed. Conceptual maps can then be used to design model structure. Conceptual maps can also be quantified in Quantitative Network Models or Bayesian Belief Networks, which combine quantitative and qualitative information. Bayesian belief networks assign values to the strength of links in the conceptual model, which can come from qualitative or quantitative information.

4.2.4 Stock Assessment Models Informed By Qualitative Information

Within assessment models, qualitative information can be incorporated into many components (Figure 5). The sections below provide further detail on how qualitative information can be used for each component.

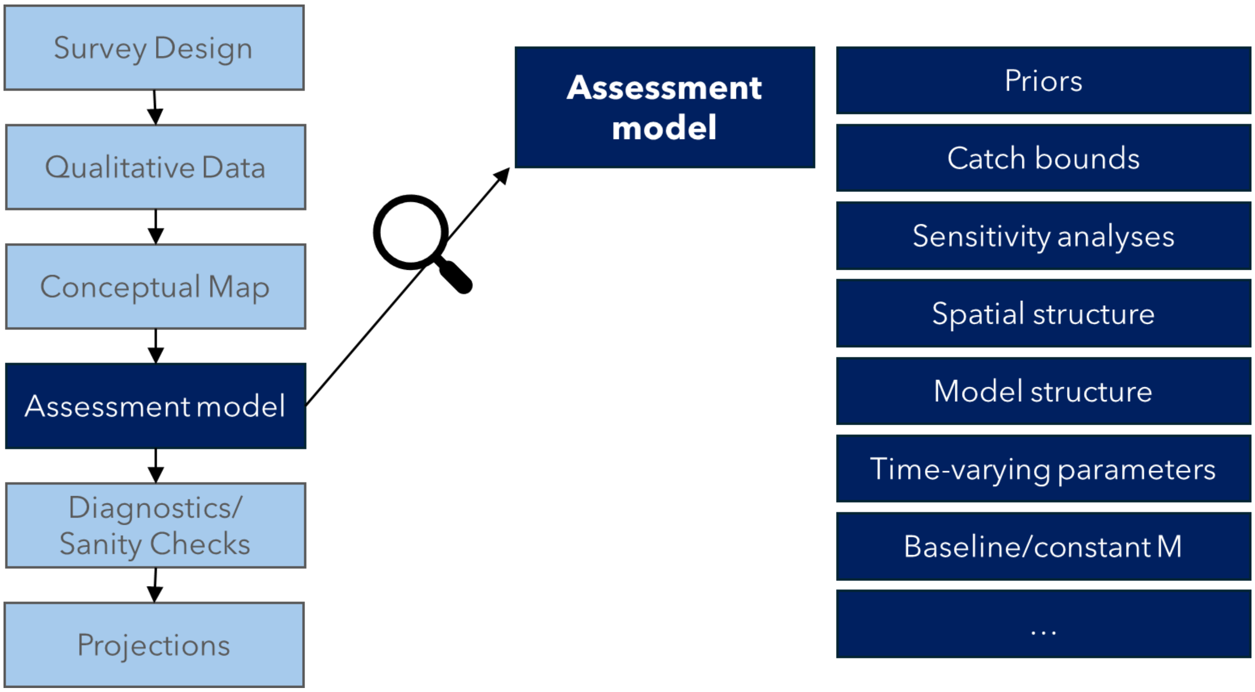

Figure 5. Focus in on the aspects of the stock assessment model that qualitative information can inform, noting this is not an exhaustive list (hence, "…").

Priors: Qualitative information is often used to construct priors in many disciplines but not as often in fisheries science. Bayesian models can incorporate qualitative information using an elicited prior (O'Hagan et al. 2006). These priors are created through various assumptions made to convert the qualitative understanding into a specific numeric prior. R packages are available to develop elicited priors, such as SHELF (Oakley and O'Hagan 2019) and makemyprior (Hem et al. 2024. As with all model assumptions, concerns regarding bias apply to the selection and specification of priors regardless of whether they are informed by qualitative or quantitative sources. Some believe that elicited priors are valuable, and others believe that elicited priors are biased (Kuhnert 2011). For example, some believe priors may bias the stock assessment results by introducing information that is not represented in the data and result in misleading stock assessment outputs (Walters and Ludwig 1994). Indeed, elicited priors do encounter challenges such as 'group think' (Esser 1998) and can miss accounting for parameter correlations (Butterworth 1995). Elicitation methods can also be biased (Johnson et al. 2010). Johnson et al. (2010) found that the validity, reliability, and responsiveness of belief-elicitation methods were not frequently evaluated and recommended that strategies to minimize bias in elicitation should be used. Concerns over bias can be partially mitigated by relying on a good Bayesian workflow with prior-posterior checks and sensitivity scenarios. Chrysafi et al. (2019) and Chrysafi and Cope (2019) elicited expert opinions to inform stock status for data-limited stock assessments. Chrysafi et al. (2019) developed a Shiny R tool to elicit expert opinion while Chrysafi and Cope (2019) found that elicited stock abundance priors performed better than priors developed from other methods.

Informing Bounds: The 3Ps Atlantic cod stock uses qualitative information from interviews with harvesters to inform bounds on catch estimates. In this assessment, a censored likelihood was used to fit landings using upper and lower catch bounds (Varkey et al. 2021). Under a fisheries science collaborative program (FSCP), harvesters were interviewed to understand the reliability of reported landings. The questions focused on aspects related to fishing practice, landing and reporting of catch and discards for different time periods in the history of the fisheries. Fisher knowledge provided insight into whether the catch might have been under- or over-reported in specific time periods. This method used both qualitative information and data-driven catch bounds for the stock assessment model. This approach also avoids the discussion about excluding data but rather allows data to be included with higher uncertainty. This same method could be used for other bounds in a stock assessment model. For example, changes in catchability can arise from changes in spatial distribution and/or temperature, and this method could then be applied to bounds applied to survey indices or catchability. Changes in survey catchability can be addressed with fully quantitative methods, but when those methods are not available, then bounds could be an option. Qualitative information on changes in survey catchability can also be addressed with elicited priors (see below). Based on a qualitative understanding of observation error, the Fraser River Pink salmon assessment also added different CVs for observation errors in different years (DFO 2025b; Glaser et al. 2025).

Sensitivity Analyses: Qualitative knowledge is also often used to inform scenarios in sensitivity analyses by informing whether a parameter (e.g. natural mortality or productivity) might be lower or higher. Based on qualitative information, it is possible to run sensitivity analyses of model consequences to possible different alternatives for some uncertainty. An example of a sensitivity analysis complemented with qualitative information was for Gulf of Maine lobster. Interviews identified non-compliance with the v-notching conservation rule for protecting spawning lobsters and a hypothesized relationship between compliance and catch (Mazur and Johnson 2020). This non-compliance was driven by changes in the lobster population and ecological understanding (i.e. increase in lobster biomass, risk of disease, etc.). Knowing the v-notching compliance was not 100%, a simulation study was then conducted and found that v-notching was a large contributor for the increasing in biomass and landings that was experienced by the lobster population and fishery (Mazur et al. 2019).

There are challenges with informing sensitivity analyses with qualitative information. For example, without quantitative information on the parameter which is the focus of the sensitivity analysis, it can be difficult to decide what to do after the sensitivity analysis is completed and had a significant impact on outcomes. Also, it is not clear how much a parameter should change in sensitivity analyses based on qualitative information. One approach could be to borrow information on plausible parameter bounds from neighbouring stocks.

Spatial structure: Qualitative information may be used to inform stock definitions and the spatial structure or extent of stocks, incorporating knowledge from fishers, Indigenous knowledge, and other sources about components of the biology, ecology, or behaviour of the target species (e.g. seasonal patterns of distribution, relative density or abundance). Qualitative information may also exist about the structure of the ecosystem (e.g. trophic relationships) or habitat (e.g. spatial extent, local changes over time).

Model structure: Stock assessment model structure captures the mathematical relationships between fish population dynamics. Most model structures account for the key population dynamics components (i.e. recruitment, mortality, and growth), but the relationships between these components and how these components are estimated varies across model structures.

Additionally, the complexity of these components and what impacts them varies across model structures. For example, some models explicitly account for ecosystem impacts on recruitment while other models estimate a single parameter to represent productivity. As previously mentioned, conceptual maps can be used to identify an appropriate model structure. However, if conceptual maps are not used, qualitative information can still be used to inform model structure. The choice of a model based on data availability is often not determined with quantitative analysis, but rather a qualitative understanding of the available information sources.

Checking/Reviewing Model Assumptions: Qualitative information can be used and is often used to determine model assumptions. For example, qualitative knowledge can be used to determine whether natural mortality should be constant or time-varying. Quantitative information may be lacking to determine model assumptions, so qualitative information can be used to fill in the gaps. For example, in the assessment for Witch Flounder in NAFO Divs. 3NO, it became clear that survey indices over 2014-2016 were decreasing faster than could be explained by the process being modelled. It was noted that these results were consistent with declining trends in other fish species on the Grand Bank and were likely indicative of ecosystem-related changes in that area. This was used as justification to support allowing the process error to increase in those three years in order to correct model misspecification and account for potential ecosystem changes (Morgan and Lee 2018).

Sanity Checking: Qualitative information can be used to “sanity check” stock assessment model output. Additionally, different model outputs can be qualitatively compared. For example, for the assessment of 3Ps cod, model output from an age-structured model with time-varying natural mortality informed by fish biological condition (i.e. ecosystem informed) and output from a SAM model where natural mortality is constant for 3Ps cod are qualitatively compared to see if the models generally agree. Interpretation between the two models can help to inform on the impact of the assumption of condition-linked mortality within the assessment and monitor for indications of whether this established link is continuing. Furthermore, qualitative information can help inform unquantifiable model uncertainty. Modern stock assessment models are sophisticated enough to be able to quantify variance around the point estimates, which is used to inform the estimation of the stock status to ensure that the management actions account for this. However, these estimates only account for a part of the uncertainty in models and resulting advice. Factors such as survey bias or unexpected environmental variation are often unquantifiable and not incorporated into the analysis. Qualitative information can help identify and communicate these unquantifiable uncertainties.

Projections: Qualitative knowledge is also often used to inform scenarios in projections. We often do not have quantitative information about what stock assessment parameters will be in the future, although sometimes these can be predicted with models. However, when there are time-varying aspects of population dynamics that are not quantifiable, qualitative information can be used to provide an approximate idea of what changes might be in the next few years (e.g. expect stability or changes in short-term growth, mortality, or recruitment based on recent temperatures, foraging conditions, etc.).

4.2.5 Management Strategy Evaluation

While an extension of the standard application of “single-species assessment”, the application to management strategy evaluation (MSE) couldn’t be overlooked, as qualitative knowledge is also often used to inform scenarios in MSEs and in closed-loop simulations (e.g. to inform Rebuilding Plans). MSEs are a powerful and flexible tool for conducting simulations to evaluate which management strategy would be appropriate under a variety of conditions. Qualitative information can help structure and inform the parameterization of the operating models (OMs; simulations of the “reality” in the analysis). In MSEs, there are several OMs that represent a variety of conditions, and qualitative hypotheses can help form the basis for the different OMs. Further, semi-quantitative information from meta-analyses or related stocks can be used to inform parameters when these cannot be estimated within the stock assessment itself. This approach has been applied to the parameterization of life-stage specific survival rates for an OM for Chinook salmon on the west coast of Vancouver Island (Brown et al. 2026).

Related to MSE, choosing between different objectives is often driven by a qualitative understanding of priorities. These qualitative understandings can be quantified and then performance metrics can be developed to serve as a basis on which to decide on management actions. However, choosing between competing objectives can still be a challenge even with qualitative and quantitative information.

4.2.6 Risk Classification Frameworks

While the focus of this workshop is incorporating ecosystem information into single-species assessment models, environmental conditions can result in risks to populations and can be captured in structured ways outside of stock assessment models when it is not feasible or practical to include them within assessment models. These may also be useful in assessments which lack a quantitative assessment model.

A standardized framework that considers imminent risks (i.e., high likelihood of poor outcomes) to fisheries associated with environmental conditions (e.g., marine heat waves) could support precautionary management and transparency in decision making. These risks can include those related to ecosystem conditions such as temperatures or anomalous prey conditions. They can also reflect population characteristics not adequately accounted for in status assessments such as a recent shift to younger ages or contraction in spatial distribution that reduce the resilience of the stock. Risks can also stem from assessment of uncertainties e.g., related to high uncertainties in data or the use of data that are not representative of the stock. Such frameworks provide a structured way to incorporate qualitative and expert evidence when direct model integration is not feasible. This approach to risk classification is demonstrated in two recent fisheries examples: North Pacific Marine Fisheries Council (Dorn and Zador 2020) and DFO-Pacific herring (Boldt et al. 2025).

Figure 6. Discussions within the Qualitative Information breakout session

4.2.7 Indigenous Knowledge

While there are multiple types of qualitative information, Indigenous Knowledge is one type that is being increasingly considered in stock assessments, and this became a focus within this breakout group. Incorporating Indigenous Knowledge requires respectful collaboration that recognizes and uplifts values and priorities of Indigenous rightsholders, and this takes time. Reciprocity is essential and is aligned with OCAP® (Ownership, Control, Access, and Possession, see: https://fnigc.ca/ocap-training/) principles. Doing this in the wrong way (e.g. in a way that is extractive and narrowly addresses DFO objectives) can be harmful and offensive. Indigenous Knowledge can support identification and prioritization of indicators for assessments and forecasts of data-limited stocks.

DFO does not have access to collect data in some fishing areas, and therefore the information from those areas comes primarily from Indigenous Knowledge to inform catch levels and stock status. As with any data source, it is important to evaluate the scale and representativeness of the information being considered for inclusion. Indigenous Knowledge is often at a fine spatial scale which may not be representative for a widely ranging stock and often cannot inform models for offshore species in deep water or for species outside of local waters, and requiring Indigenous Knowledge can be counterproductive in these cases.

For respectful consideration of Indigenous Knowledge, it should be considered throughout the science process. Within the DFO Stock assessment process this may include participation in the development of Canadian Science Advisory Secretariat (CSAS) meeting Terms of Reference, and Steering and/or Technical Committees which may be made inclusive for Indigenous collaborator(s). For example the November 29-30, 2018 Regional Peer Review on the Biophysical and Ecological Overview of a Study Area within the Labrador Inuit Settlement Area Marine Zone (DFO 2021) was co-led with the Nunatsiavut Government. However we note that “meeting fatigue” can also be an issue; knowledge holders cannot meet with and be involved with all projects/assessments

There are a few examples within DFO where Indigenous Knowledge has been incorporated into the stock assessment process. Indigenous Knowledge has been used to inform survey design and stock structure. In the Arctic region, Indigenous Knowledge often informs data collection, sampling, and monitoring design. This qualitative information is foundational in the design of monitoring programs and informing stock structure, which can then inform quantitative modelling. For the Inuit Circumpolar Council, there is a mandate to include Indigenous Knowledge in advice. A notable success story involves Beluga assessments in Alaska, where sampling was revised by working collaboratively with Inuit and resulted in higher and more consistent estimates of biomass.

A participant shared an example from their early career prior to joining DFO in which they worked on a habitat restoration project that included qualitative information – specifically Indigenous Knowledge. Recognizing that answering specific scientific questions about fish habitat use required engaging Indigenous collaborators in ways that extended beyond the researcher's formal skills and training, they engaged a social scientist during project design. This helped to shape a semi-structured phone survey that was flexible, respectful of participants time and responsive to community guidance. At the recommendation of the Indigenous partner organization, interviews were led by a local community member with the researcher participating and asking clarifying questions as needed. This approach supported more natural dialogue and improved the relevance and richness of the information gathered. The example also highlighted practical considerations that are often overlooked including the cumulative burden placed on a small number of knowledge holders who are repeatedly asked to participate in projects and the importance of reciprocity. Early engagement allowed the research team to adapt their approach to better reflect the ways in which knowledge holders understood and shared information about their environment. These adjustments improved the quality of the information collected and its relevance to the project objectives while reenforcing that meaningful engagement is an iterative learning process. This example illustrates that even with experience and good intentions, qualitative data collection from people requires very specific expertise and ongoing learning. Early collaboration with social scientists where possible will improve project design, reduce unintended harms and support the respectful and effective inclusion of qualitative information. It also underscores that developing confidence and competence in this area is a gradual process and that many scientists, even those with prior experience, may not be prepared to design or lead qualitative data collection for stock assessment processes.

4.2.8 General Considerations

Discussion stressed the need to document the qualitative information that we use and how it is applied in stock assessments. This break-out group identified that qualitative information is frequently used in DFO stock assessments, and it is often wrapped into choices on model assumptions and data collection. We should be transparent about how qualitative information is used and where it is from (e.g., from fishers, Indigenous Knowledge Systems, etc.).

When collecting Indigenous Knowledge or fishers' knowledge, working with social scientists should be considered from the outset as collecting qualitative data has its own best practices and methodological requirements. Stock assessors are often trained through quantitative science pathways and have limited formal training in qualitative methods which can create uncertainty about how to engage knowledge holders. Qualitative information is best elicited with guidance from social scientists.

Experts with qualitative knowledge should be included in the assessment process early and often. One benefit of incorporating qualitative information into stock assessment models is that it can support a participatory approach. A participatory approach works best when participants are included at the beginning of a study and throughout the study. Wedemeyer-Strombel et al. (2019) found that participatory action research provided fine-scale information, supported mutual learning and leadership, incorporated qualitative information, and encouraged local participation in conservation.

4.3 APPROACHES FOR CONSIDERING THE SPATIAL SCALE OF ENVIRONMENTAL DRIVERS WHEN INCLUDING THOSE DRIVERS IN ASSESSMENTS

Participants: Matthew Robertson, Divya Varkey, Greig Oldford, Hannah Munro, Jaclyn Cleary, Krista Baker, Nathan Hebert, Nick Gullage, Stephanie Boudreau, Travis Tai, Yihao Yin, Daniel Howell

The breakout session which was held across days 3 and 4 and hosted by Matthew Robertson, explored approaches for incorporating spatial and environmental variability into stock assessment models. Participants discussed why spatial patterns need to be considered, how to identify relevant data, and strategies for integrating spatial and environmental considerations in stock assessment models and frameworks. The group developed a decision-tree (Figure 7) and guidance to support scientists who have identified a population process (e.g., maturity, weight-at age) that is hypothesized to vary spatially that should be accounted for in the stock assessment model (framework).

4.3.1 Spatial Process Hypothesis

Traditional single-species stock assessments often incorporate environmental covariates as time-series to explain temporal variation in demographic processes. However, environmental effects frequently differ in strength, magnitude, and direction across fine spatial scales and life stages. Ignoring this heterogeneity can misrepresent reality, affecting estimates of recruitment, mortality, growth, and maturity. Spatial variability can influence productivity and management outcomes, especially under changing climate conditions.

Once a process (e.g. weight, age, diet, maturity) has been identified as potentially being spatially variable, for example asynchronous recruitment (Kumar et al. 2019), the next step would be to decide whether it is creating an issue in the stock assessment model that could be accounted for.

Spatial considerations can be incorporated at multiple points:

- Inputs: Modify weight-at-age, maturity ogives, and abundance indices to reflect spatial patterns. For example, modelling spatiotemporal weight-at-age variation could improve mean estimates or, spatially standardized indices could replace design-based estimates where strata misalign with species ecology.

- Parameter estimates: If spatiotemporal variability is identified in a population process, random effects can be used to implicitly account for spatial structure. For example, identifying spatiotemporal variation in predation mortality or body condition may indicate a need to allow natural mortality to vary annually as a random effect (e.g., Robertson et al., 2025).
- Covariates: Environmental drivers can be included explicitly. Iterative approaches and verification that model performance justify including the spatial or spatiotemporal processes were stressed by the participants. Acknowledgement that variables such as temperature, salinity, and habitat type influence biological processes at different spatial and spatiotemporal scales – for example, bottom type is critical for invertebrates, yet legacy survey strata designed for other target species often ignore this factor. Examples also included scallop growth models which were improved by including spatial temperature fields (Yin et al. 2022) and shrimp assessments standardizing CPUE by accounting for sea-ice availability (Baker et al. 2025).

Data Considerations: The spatial process hypothesis will guide data selection and modelling. A critical early step is assessing the availability and resolution of spatial and non-spatial datasets to support your hypothesis (e.g., Kumar et al. 2019, Hebert et al. 2024). Sources include empirical surveys, modeled datasets, and repositories (e.g. marea, pacea, gslea, ERDDAP, and CIOOS). Participants emphasized the need to check for sampling biases (e.g., vessel effects, swept area) and ensure data resolution matches hypothesized processes. Some datasets are rich, while others are sparse or biased requiring caution in interpretation. Cataloging available oceanographic and ecosystem data was identified as a priority to streamline integration.

Spatial Variability, Analysis, and Understanding: Several modeling approaches were discussed when identifying spatial and spatiotemporal process variability, including GLMMs, sdmTMB, tinyVAST (see the VAST decision-tree in Thorson 2019), INLA, spatial GAMs, and geostatistical methods (e.g., Moran's I for spatial autocorrelation). Decision frameworks such as directed acyclic graphs (DAGs) and causal inference tools were recommended to structure hypotheses and guide model selection. Participants stressed starting simple by correlating environmental variables, testing collinearity, and exploring spatial trends, before increasing model complexity. Diagnostics like residual mapping (e.g., looking for spatial patterns from non-spatial models) and cross-validation are essential for evaluating whether spatial models improve fit, understanding of process, and forecasts (e.g., Yin et al. 2022, McDonald et al. 2023, Grüss et al. 2025, Howell et al. 2013).

Management Relevance: The group highlighted the importance of translating spatial insights into tactical and strategic advice. This includes quota adjustments, spatial closures, and supporting operational decisions to reduce bycatch (e.g., DFO 2025c). Communication with managers should clearly outline what environmental and spatial information is included (implicitly or explicitly), what is excluded, and why. Participants noted that complexity should only be added if it provides meaningful improvement for science or management.

Challenges, Recommendations, Takeaways:

- Key challenges include limited spatial resolution in historical data, risk of overcomplicating models, and the need for training on spatial diagnostics.
- Start simple and iterate: Begin with exploratory analyses and only add complexity when justified.
- Communicate explicitly: Report what is included, what is not, and the rationale.
- Evaluate benefits: Use model selection criteria, diagnostics, and simulation testing to assess whether spatial models improve fit, reduce process error, or enhance forecasts. Running a spatial assessment model is a lot of work, does it make sense?
- Spatial and ecosystem information is already incorporated implicitly in many assessments, make sure these implicit assumptions are communicated.
- Spatial analyses do not always need to be embedded in the assessment model; they can improve process understanding and inform hypotheses.
- An important goal is to balance scientific rigor with operational feasibility, ensuring that spatial modeling efforts lead to actionable insights for fisheries management.

4.3.2 Decision-tree steps, guidance, and considerations:

A decision-tree was developed to guide the consideration of EVs with an identified spatial process, and is outlined in Figure 7, with steps detailed here.

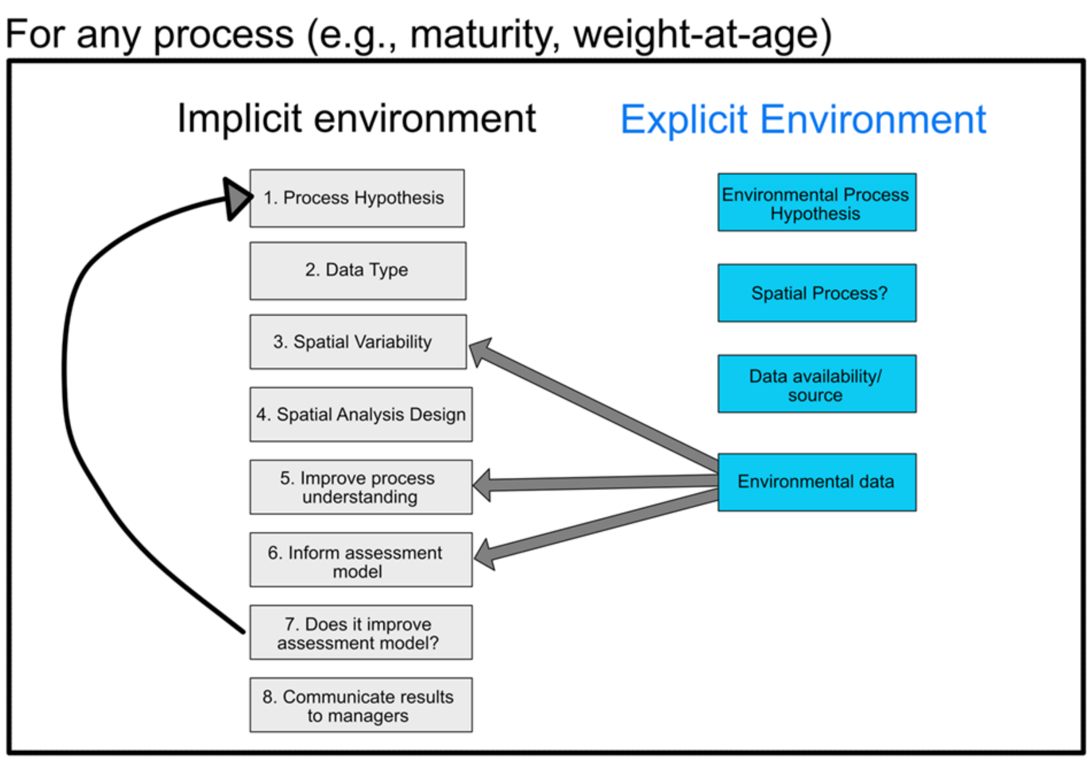

Figure 7. Decision tree for when to consider and incorporate implicit and explicit environmental data into stock assessment models and frameworks with a spatial process

1. **Do we have a process (e.g., weight/condition, maturity, abundance/biomass index, age/length, diet, etc.) that we think varies across space <u>and</u> is a problem for the assessment?**
    a. Stock assessment model input
    b. Stock assessment model output (e.g., recruitment, M, etc.)
    c. Spatially varying environment
    d. Ecological hypotheses

2. **What do the data look like (i.e. are they of a relevant spatial resolution for the assessment)**
    a. Non-spatial (e.g. fishery dependent, not enough samples across space or time)
        i. Ecosystem data (environment & multispecies) – empirical, modeled, composite indices
    b. Spatial (fishery dependent or independent)
        i. Ecosystem data – empirical, modeled (e.g., marea, pacea, gslea, ERDDAP, CIOOS)

3. **Do we see different spatial/spatiotemporal process variability – empirical**
    a. Types of spatial approaches for identifying – spatial aggregation, geostatistical indices (e.g., Moran's I)
    b. If variable, does it align with environmental variability?
        i. Based on expert opinion
        ii. Residuals from non-spatial model

4. **Does the spatial process model indicate that there are spatial differences?**
    a. Types of "spatial" approaches that produce estimates – sdmTMB, tinyVAST, INLA, glmm, spatial gamm, spatial aggregation, spatial interpolation (e.g., kriging), see tinyVAST documentation and EAFM methods toolbox.
        i. Only increase resolution as needed (e.g., model selection)
        ii. Check diagnostics/assumptions (e.g., spatial trends in residuals)
            - Consider sampling bias covariates (e.g., vessel, swept area)

5. **Does accounting for these differences improve process understanding?**
    a. Compared to initial estimates (e.g., non-spatial model, design-based estimates)
    b. If yes? Are there environmental relationships?
        i. Add covariates (how to model select?)
    c. Try and use this to advise fisheries management – quota vs operational decisions

6. **How can we use spatial trends to inform the assessment?**
    a. Modify data range (e.g., space, time) to represent current spatial processes
        i. Need to keep if they contribute to spawning/breeding population
    b. Modify population structure
        i. Split assessment model
        ii. Create spatially resolved assessment model
    c. Modify process inputs (e.g., weight-at-age) and abundance/biomass indices

    i. Different for indices vs process inputs
    ii. For process – marginalize across local abundance/biomass, marginalize across space
    iii. Modify input to account for sampling bias
    iv. Modify input/index uncertainty
  d. Add process error (e.g., mortality, recruitment)
  e. What happens if env effects are spatially localized
    i. Use random effect and/or covariate from important location to inform process (e.g. Natural Mortality (M), numbers-at-age (NAA), recruitment)

7. **Does incorporating these estimates improve assessment model fit?**
  a. Does the model change:
    i. Model selection criteria
    ii. Derived quantities (e.g. SD)
    iii. Model estimates (e.g. SD)
    iv. Observation error (trend, SD)
    v. Process error (trend, SD)
    vi. Diagnostics
  b. Can we use spatial models to improve forecasts?
    i. Performance metrics in simulation
    ii. Spatially project inputs?
  c. Was the assessment model improvement "enough"?
    i. How to decide what is enough of an improvement?

8. **How to ensure this gets back to managers**
  a. Communicate efficiently in all the ways the environment is included implicitly and explicitly (e.g., time-varying weight at-age, spatial survey adjustment, process error, covariates).
  b. Was assessment model improvement enough to result in an operational change?
  c. Communicate spatial or environmental concerns that could be important (e.g., process hypotheses) but not modelled due to resource or operational limitations.
  d. Can the model provide answers to management related to specific areas and make environment informed advice (either quantitative or qualitative)?

4.4 USE OF SIMULATION AND DFO'S HIGH POWER COMPUTING (HPC) RESOURCES

Participants: Catarina Wor, Aaron Adamack, Meghan Burton, Mackenzie Mazur, Carrie Holt, Andew Harbicht, Kevin Hedges, Xinhua Zhu, Divya Varkey, Robyn Forest.

This breakout room took place on day 4. In addition to workshop participants, a local experienced user of DFO's HPC resources (Rajeev Kumar, DFO NL) was included in this session to share expertise.

Consideration of EAFM in fisheries science and stock assessment often involves the use of simulation modelling and advanced statistical computing. The inclusion of environmental covariates, time-varying dynamics and ecosystem modelling in stock assessments, management strategy evaluations and recovery potential projections greatly increases the need for computing power. These analyses are often critical to the Department's mandate to meet the requirements of the Fish Stocks provisions under the revised Fisheries Act, the Species at Risk Act and various international fisheries management agreements (e.g. ICES, NAFO, Pacific Salmon Treaty). Given the expanding scale and complexity of our analytical methodologies, and the necessity to deliver crucial information in a timely manner, there is an increasing need for stock assessment scientists to access high powered computing resources within the Department. The risks of not having high-powered computing include fisheries management advice that does not account for time-varying dynamics, e.g., related to climate impacts or include closed-loop simulations that are often necessary to tease apart the complex trade-offs in management.

At DFO, High computing power is currently available under the General Purpose Science Computing (GPSC)-high performance computing (HPC) services. The GPSC-HPC system is configured to optimize computing resources for the user, and Science staff have onboarding access provided by the Ecosystems and Oceans Science coordinator. However, the coordinator cannot provide targeted support for optimization of code on the GPSC-HPC system as this is beyond the scope of their expertise. Most of the analyses currently used in stock assessment models are done in R. With that in mind, the proposal of this break-out group was to gather current and prospective users of the GPSC-HPC to exchange ideas, tips and tricks on how to increase efficiency and understanding in using this resource. The topics covered in this break-out group were:

- How to get a GPSC-HPC account (i.e. overview of the forms and process)
- How to log into the system and set up your user directory
- How to set up your R code to run on the GPSC-HPC using the R package rslurm (Marchand et al. 2023)
- Overview of batch scripts
- Several examples of using GPSC were presented and discussed.
- Using RStudio on the GPSC-HPC
- How to reach out for help

Through discussion during this breakout group, we found that there are multiple ways to get your code working on the GPSC-HPC, and it may depend on your functions and desired output.

This breakout group will hopefully promote more efficient and widespread use of the GPSC-HPC resources and enhance the development, use, and adoption of EAFM across Canada.

5. PLENARY & WORKSHOP WRAP-UP (DAY 4)

A short plenary session was held during the second half of the afternoon on Day 4. Leaders from each of the breakout groups presented a summary of the main outputs from their group, including recommendations.

The first three break-out groups each produced a framework or guidelines to help structure and guide future work on the incorporation of environmental considerations in assessments and assessment models, as can be seen in the previous sections. While these frameworks were formed independently of each other, participants noted the significant overlap in proposed processes and that areas where these decision frameworks focused on particular issues (e.g. M vs. qualitative information) naturally connect in the broader development of assessment models and MSE.

A short general discussion about future TESA workshops on EAFM followed, with further input collected in a post-workshop survey of participants. Recommendations stemming from that discussion are presented below.

The workshop concluded with general instructions from the co-chairs concerning finalization of the present proceedings document and best wishes for safe return travels for participants from outside Newfoundland.

Figure 8. Plenary discussions held in the Auditorium of the Northwest Atlantic Fisheries Centre, St. John's, NL.

6. OVERALL CONSIDERATIONS

The breakout group and plenary discussions identified that DFO is already doing a lot in terms of incorporating EVs into assessments, but they also identified key challenges going forward. The quality of DFO contributed talks and high level of engagement by participants demonstrated a keen interest in the practical implementation of EAFM in DFO. The guidelines put forward by the breakout groups constitute a practical basis for EAFM implementation, and highlight the vast array of considerations that are already given to the inclusion of environmental information in stock assessment. Overall, they consistently describe a common, underlying general process to include ecosystem variables into single species stock-assessment models that could be summarized as follows:

- **Identifying a need to explore environmental variables within a given assessment**. The motivation for this can be very different, depending on, e.g. the stock, life history, ecosystem, application, research priorities of the Department, etc. In many cases, action to include EVs in a single species stock assessment model will be “triggered” by an issue with an existing assessment used for tactical management advice. However, EV inclusion may be part of a broader research program or aimed at furthering our understanding of stock drivers or ecosystem change/impacts.

  Alternatively, a change in the ecosystem a stock is found in may be motivation to explore the inclusion of EV. Stocks do not exist in a vacuum; changes to their dynamics can be seen as driven by processes that are singular to the stock being assessed, or they can be driven by processes that are ecosystemic in nature, and that affect multiple stocks/species within a given ecosystem. Ecosystem summaries can be used to provide an overall synopsis of the ecosystem changes that have occurred, and to identify large scale ecosystem patterns that may affect multiple stocks, and that can be relevant/impactful on the target stock. If large scale ecosystem drivers cannot be identified, it follows that the processes affecting the stock dynamics would be expected to be more narrow in scope, and likely stock-specific.

Not all stock assessments will be improved by the inclusion of EVs, and there is a significant workload required to properly explore this. Do not underestimate the importance of this scoping step.

- **Identifying linkages**. Once potential, relevant processes have been narrowed down, a working understanding of how these processes interact should be constructed. To this end, the development of causal, conceptual models on how environmental/ecosystem processes are expected to impact the target stock is recommended. Incorporating ecosystem information in an effective and defensible way requires the construction of working hypotheses. While a mechanistic understanding of these linkages is advantageous, it may not always be necessary where strong associations are expected. “Shotgun approaches” (throw everything at it and see what sticks) would likely distract from focusing on plausible pathways and should generally be discouraged.

- **Identifying relevant data**. Identify relevant information/indicators for the processes/drivers included in the causal conceptual models. Consideration should be given to availability, resolution, spatial and temporal coverage, and reliability of these data sources. Availability of forecasted conditions may be relevant when considering multi-year projection scenarios, rebuilding timelines, MSE, etc.

- **Defining working hypotheses**. Based on the available data, explicitly describe the hypotheses that can (and cannot) be tested/implemented in the assessment model. It is important to document when a plausible hypothesis cannot be evaluated due to lack of sufficient or appropriate data. This type of limitation does not invalidate the hypothesis and, hence, the eventual interpretation of results.

- **Selection of suitable methodologies**. For those hypotheses that can be evaluated, select the most appropriate method(s) to do so. Depending on the data available, the nature of the hypotheses, and the specific type of application intended to be supported by the assessment model,these methods may include (this list is not exhaustive, in no specific order, and its items are not necessarily mutually exclusive):
    - Implementation of time-varying processes in the model through time-varying process error deviations in rate (e.g. M deviations) and state variables (e.g. cohort deviations). This represents an implicit consideration of ecosystem information. In these cases, the patterns over time in process error could also be compared with trends of relevant ecosystem indicators to further explore causal linkages.
    - Inclusion of ecosystem variables as covariates in the assessment model. This represents an explicit consideration of ecosystem information. The inclusion of covariates would be expected to explain part of the process error (when applicable), grounding the model in more specific ecological mechanisms/processes.
    - Scenario evaluation considering levels of the covariate or levels for the stock vital rates (i.e. model parameters) expected to respond to the changes in ecosystem

conditions. These scenario evaluations represent one possible way of dealing with the projection of covariates.
  - Closed-loop simulation exercises to understand how different management strategies could affect how the stock may respond under different ecosystem scenarios and/or ecological hypotheses.
  - If ecosystem variables cannot be directly integrated into the model, or a model cannot be developed, post hoc risk-assessment frameworks could be developed to adjust the risk levels and science advice based on ecosystem considerations.

- **Model implementation and evaluation of results.** The evaluation of model results will be specific to each implementation, however, there are some general elements that are likely to hold across cases, including:
  - Evaluation of model fit using a battery of standard diagnostics (e.g. goodness of fit statistics, information criteria indices, analyses of residuals, etc.).
  - Consideration of the ecological/biological plausibility of the estimated parameters and results obtained (i.e. the hypothesis evaluated may be plausible, but the estimated parameters and results also need to make ecological/biological sense).
  - Analysis of the results in terms of their implications for interpreting stock dynamics and identifying stock drivers, including ecosystem ones.
  - If projections and evaluation of management options are part of the analysis, consideration of how the ecosystem drivers and management options may interact to define future trajectories of the stock.
  - Whether the inclusion of EVs has improved the assessment model and resulting advice, and is operationally feasible going forward.

- **Generation of stock advice.** While conducting the scientific analysis and evaluating model(s) results represent the core of the science work towards integrating ecosystem information into stock assessment models, the purpose of this work is to generate science advice that can effectively inform management decisions. This requires translating highly technical work into descriptions of the work done – including its management implications – that can be clearly and unambiguously understood by managers and stakeholders. Clearly communicate where EVs have been used to inform advice, and where we are unable to do so, focusing on the practical implications of inclusion (or not) in the interpretation of results. As with any stock assessment, communicate advice in terms of risk. Proper contextual interpretation of these risks is essential for their effective use, particularly when considering scenarios under different ecosystem conditions, which have different expectations when considering short- or long term outcomes for the stock, or when considering interactions among species/stocks.
  - While general recommendations have been identified for the generation of stock advice, their application to advice and communication was largely considered to be outside of the scope of workshop discussions, given their complex nature, and further discussions are recommended to allow for a complete consideration of this key aspect.

7. RECOMMENDATIONS

Participants' engagement clearly demonstrated an interest in this type of workshop. Participants noted that the in-person format was key to effective collaboration, and the inclusion of external experts provided a broader scope of knowledge. Participants identified the value of this workshopand suggested that recurring workshops of this nature would be useful to advance EAFM.

Recurring themes identified during plenary and break-out groups pointed to possible topics for future workshops or TESA courses. These included:

- Communicating risk-based EV-informed science advice. Such a workshop could be explored as a collaboration between TESA, the National EAFM working group, and those involved in the review of DFO's Precautionary Approach Framework.
- Gaining – and incorporating into assessments – a more mechanistic understanding of EV effects. Notably causal models are (re)emerging as a powerful approach for doing so (e.g. Champagnat et al. 2025).
- Practical considerations in including EVs in assessment models including bias-variance trade-offs (when and how much to include), confounding effects on different modelled processes, how they might affect reference points, and whether they are useful only for hindcasting (and not forecasting).
- Consideration of ecosystem information in index-based or data limited assessment methods (e.g. "stop-light" approaches, risk frameworks)
- Addressing and communicating the nature of variation in natural systems (e.g. weather, climate, productivity), and interactions among physical, chemical and biological properties or processes.

The *EAFM Methods Toolbox* was discussed during this workshop as a resource for EV inclusion. This Toolbox is identified as an "evergreen document," however the process or mechanism by which suggestions for additions to this toolbox could be submitted or actioned within DFO is unclear. Generally it was noted that the toolbox would be improved by inclusion of tools focused on the treatment and inclusion of qualitative information in assessment models.

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APPENDIX A. WORKSHOP AGENDA AND LIST OF PARTICIPANTS

Note: This is the agenda as proposed at the start of the workshop, noting it would remain fluid depending on the direction of discussions. Additional plenary discussion was added on the afternoon of day 2, with the start of breakout groups moved to the morning of day 3.

Methods for Incorporating Ecosystem Information into Single-Species Stock Assessment Models TESA Workshop, November 24-27, 2025

Chairs: Andrew Edwards (PAC), Laura Wheeland (NFLD), and Hugues Benoît (QUE). Northwest Atlantic Fisheries Centre (NAFC), St. John's, NL.

Agenda

Monday November 24 (NAFC Auditorium)	
9:30 am	Welcome, Introductions, Review of workshop objectives
Contributed talks by DFO scientists (available on MSTeams)	
10:15	Introduction to the EAFM Methods Toolbox (Hugues Benoît, QC)
10:30	An approach for providing stock advice under ecosystem impacts with data and model limitations (Meghan Burton, PAC)
11:00 – Health Break	
11:15	Using an index of biological condition to inform time varying natural mortality of Atlantic Cod in 3Ps. (Divya Varkey, NL)
11:30	Evaluating the impact of time-varying parameters under varying quantities of age data (Mackenzie Mazur, PAC)
11:45	Developing CSAS advice for Reference Points in Non-Stationary Conditions under the Fish Stocks Provisions and the Precautionary Approach (Catarina Wor, Divya Varkey and Carrie Holt)
12:00 – Lunch (not provided)	
1:00 pm	**Keynote #1:** Recent progress towards EBFM in Europe – and some stumbling blocks. Daniel Howell, Institute of Marine Research, Norway
2:00pm	**Keynote #2:** Myth, mechanism, and misattribution in Ecosystem-Based Fisheries Management. Matt Robertson, Marine Institute, Memorial University of Newfoundland
3:00pm – Health Break	

3:15pm	**Keynote #3:** Environmental Information in Stock Assessments of New England Groundfish. Steve Cadrin, University of Massachusetts, Dartmouth
4:15 pm	Discussion
5:00 pm	End for the day

Keynote seminars by each of the external invited experts were broadcast Nationally via ZOOM as part of the S. Plourde Memorial EAFM seminar series.

Tuesday November 25	
Morning: NAFC Auditorium Contributed talks by DFO scientists (available on MSTeams)	
9:00am	Review of Day 1, Set up Day 2
9:30	salmonMSE: a decision-support tool for Pacific salmon accounting for within-population life-history diversity and environmental drivers (Carrie Holt, PAC)
9:45	Time-varying models for Pacific salmon: estimation, model selection and closed-loop simulations (Catarina Wor, PAC)
10:00	Incorporation of hydroclimate and exploitation impacts into monitoring, assessment and management of anadromous Dolly Varden population productivity (Xinhua Zhu, ARC)
10:15	Modelled reconstructions of marine environmental and ecosystem variables: trends, causal inference, and recent applications in the Pacific Region (Greig Oldford, PAC)
10:30 – Health Break	
10:45	Drivers of Pacific Hake recruitment -- lessons learned from trying to operationalize the research (Andrew Edwards, PAC)
11:00	Exploring environmental effects on fish stock recruitment - tools to bolster EAFM and contributions toward CSAS reports (Travis Tai, PAC)
11:15	The use of ecosystem variables in 2J3KL Capelin assessments (Aaron Adamack, NL)
11:30	Linking Prey and Predators: How Capelin Informs the Northern Cod Stock Assessment (Paul Regular, NL)
11:45	Discussion / breakout logistics
12:00 – Lunch (not provided)	
1:00	Break-out group work. Groups should take a 15 minute health break at a time that suits the group. (Breakout rooms: N20-122, N20-104, N20-108, N20-109)

4:30 pm	Plenary discussion and plan for day 3. (Auditorium)
5:00 pm – End for the day	
Evening – Group Dinner, 6:30pm, Yellowbelly Brewery 288 Water Street, St. John's NL	

Wednesday November 26, 2025 Breakout rooms: N20-122, N20-104, N20-108, N20-109	
Morning	Break-out group work
10:30	Health Break
12:00	Lunch (not provided)
Afternoon	Break-out group work
3:00 pm	Health Break
4:30 pm	Plenary discussion and plan for day 4.
5:00 pm	End for the day

Thursday November 27, 2025	
Morning	Break-out group work, including drafting of short summary text for the workshop report (N20-122, N20-104, N20-108, N20-109)
10:30	Health Break
12:00 – Lunch (not provided)	
1:00 pm	Break-out group “show and tell” (Memorial Room)
2:45 pm	Health Break
3:00 pm	Plenary discussion (Memorial Room). Recommendations, next steps and future work.
5:00 pm – Workshop close	

List of workshop participants

Participant	Affiliation
Adamack, Aaron	DFO, Newfoundland and Labrador Region
Baker, Krista	DFO, Newfoundland and Labrador Region
Benoît, Hugues	DFO, Quebec Region
Boudreau, Stephanie	DFO, Gulf Region
Burton, Meghan	DFO, Pacific Region
Cadrin, Steve	University of Massachusetts, Dartmouth, USA
Cleary, Jaclyn	DFO, Pacific Region
Edwards, Andrew	DFO, Pacific Region
Forrest, Robyn	DFO, Pacific Region
Gullage, Nick	DFO, Newfoundland and Labrador Region
Harbicht, Andrew	DFO, Gulf Region
Hatefi, Fatemeh	DFO, Newfoundland and Labrador Region
Hebert, Nathan	DFO, Maritimes Region
Hedges, Kevin	DFO, Arctic Region
Holt, Carrie	DFO, Pacific Region
Howell, Daniel	Institute of Marine Research, Bergen, Norway
Koen-Alonso, Mariano	DFO, Newfoundland and Labrador Region
Mazur, Mackenzie	DFO, Pacific Region
Munro, Hannah	DFO, Newfoundland and Labrador Region
Neville, Victoria	DFO, Newfoundland and Labrador Region
Oldford, Greig	DFO, Pacific Region
Regular, Paul	DFO, Newfoundland and Labrador Region
Ricard, Daniel	DFO, Gulf Region
Rideout, Rick	DFO, Newfoundland and Labrador Region
Robertson, Matt	Marine Institute, Memorial University of Newfoundland, Canada
Sylvain, François-Étienne	DFO, Gulf Region
Travis Tai	DFO, Pacific Region
Varkey, Divya	DFO, Newfoundland and Labrador Region
Wheeland, Laura	DFO, Newfoundland and Labrador Region
Wor, Catarina	DFO, Pacific Region
Yin, Yihao	DFO, Maritimes Region
Zhu, Xinhua	DFO, Arctic Region

APPENDIX B. ABSTRACTS FOR CONTRIBUTED AND INVITED PRESENTATIONS

(ordered according to the Agenda)

Introduction to the EAFM Methods Toolbox (Hugues Benoît, Quebec Region)

Fisheries and Oceans Canada's (DFO) national Ecosystem Approach to Fisheries Management (EAFM) Working Group developed a National EAFM Science Methods Toolbox and published an associated user's guide in 2025. The 'toolbox' is best viewed as an indexed searchable catalogue of methods and approaches for scientific support of EAFM. Methods are organized according to broad classes and users can search according to research objectives, management considerations and input data requirements, for instance, to identify candidate methods. Brief descriptions and key associated references for each methods are available in the Toolbox User's Guide, which has been published as a DFO technical report. The 'toolbox' is not considered to constitute an exhaustive inventory of all available methods relevant to EAFM. Rather, it is expected to remain 'evergreen', with periodic updates to reflect emerging best practices. The present workshop is expected to contribute to that end.

An approach for providing stock advice under ecosystem impacts with data and model limitations (Meghan Burton, Pacific Region)

Many marine invertebrate stocks are not managed using traditional stock assessment models which makes it more difficult to include ecosystem impacts quantitatively. However, invertebrates can be especially sensitive to environmental conditions and predation as many are sessile. There needs to be a way to incorporate ecosystem impacts on these species indirectly so that even with lack of data, qualitative information (i.e. expert knowledge) could be used to test the robustness of these fisheries under a wide range of possible scenarios. Closed-loop simulation through openMSE allowed us to incorporate ecosystem impacts by simulating a range of potential ecosystem impacts identified through expert knowledge. This simulation framework provides an approach to understand how robust management options are to these impacts, when directly including ecosystem impacts in a stock assessment model is not an option. It can also help triage what ecosystem impacts your stock is likely to be most vulnerable to and where to focus your resources. This work shows that closed-loop simulation can be a viable option to account for ecosystem impacts for invertebrates and other species when these impacts cannot be modelled directly due to data and/or model limitations.

Using an index of biological condition to inform time varying natural mortality of Atlantic Cod in 3Ps. (Divya Varkey, Newfoundland and Labrador Region)

Fisheries stock assessments traditionally assume that natural mortality (M) is constant across all ages and years and typically set at a value of 0.2. For the southern Newfoundland stock of cod (3Ps cod), prior assessments indicated an increase in total mortality, necessitating models that incorporate time-varying M. We developed models with time-invariant and time-varying M. A time-invariant base natural mortality level of M=0.3 was chosen because estimates from neighboring cod stocks and tagging data suggested M levels higher than the traditional 0.2, and this value facilitates similar base levels across both time-invariant and time-varying modeling approaches. The methodology for time-varying M hypothesizes that M is a function of fish condition, specifically hypothesizing that low 'energetic condition' following the spring spawning season increases the fish's vulnerability to environmental stressors. A condition-based index of M (*Mc*) was developed using fish length and weight data from DFO RV surveys (starting 1978) and sentinel surveys (starting 1995). This model accounts for seasonal variations in condition (low in spring, high in late summer). For applying in the fish stock assessment model, the *Mc* index was normalized; this normalization involves scaling the *Mc* index using the mean and standard deviation calculated over a reference period (1978 to 2012). This scaling allows the covariate to be treated as an anomaly, resulting in M estimates above or below the baseline M=0.3. Parameters *mpar* estimated within the assessment quantify the influence of the covariate on the trend on M: an estimate close to zero suggests little influence. M positively tracks the normalized Mc covariate trend when mpar is positive; a higher mpar value indicates tighter alignment with that trend. The *mpar* parameter was estimated separately for two age groups (immature and mature) to enable different responses to changes in fish condition for the two age-groups.

Evaluating the impact of time-varying parameters under varying quantities of age data (Mackenzie Mazur, Pacific Region)

Ecosystem-driven changes are increasingly affecting fish stock dynamics, yet integrating these effects into single-species stock assessment models remains challenging, especially when data are limited. This study uses closed-loop simulations to evaluate how missing age data, combined with different age-structured model assumptions (constant parameters vs. random effects) affect the performance of stock assessments for Petrale Sole in British Columbia under time-varying life histories. Results highlight the importance of age data in capturing ecosystem impacts and informing management advice under changing environmental conditions. Future work will extend this framework to explore the performance of index-based assessment methods under ecosystem-drive changes.

Developing CSAS advice for Reference Points in Non-Stationary Conditions under the Fish Stocks Provisions and the Precautionary Approach (Catarina Wor [Pacific Region], Divya Varkey [Newfoundland and Labrador Region] and Carrie Holt [Pacific Region])

Reference points are a key component for the implementation of DFO’s “A fishery decision-making framework incorporating the precautionary approach” (i.e. the PA Policy) which serve as basis for interpreting the Fish Stocks provisions (FSPs) under the revised *Fisheries Act*. Given the increased impacts of changing conditions on the dynamics of exploited marine resources, Strategic Policy has requested national science advice on a transparent framework for evaluating whether changing environmental or ecosystem conditions indicate that existing PA reference points may no longer be appropriate. The objective of this science advice process is to produce two working papers. The first providing the scientific framework that contains guidance on developing reference points under non-stationary conditions, including evaluating evidence, assessing risks of different management options, and the conditions when reference points should be changed. The second working paper being a compilation of tools and example scenarios of evaluation of reference points under non-stationary conditions within the Canadian context. Any research documents or Science advice arising from this process can be added to the growing inventory of tools and resources available to support DFO's implementation of an ecosystem approach to fisheries management.

Keynote #1: Recent progress towards EBFM in Europe – and some stumbling blocks. Daniel Howell, Institute of Marine Research, Norway

This talk will give a brief overview of some recent progress towards a better implementation of EBFM in Europe. This will not attempt to be a comprehensive review, but rather focus on topics which have seen recent intensive research focus, covering both ecosystem realism in assessments and single species advice and progress towards better advice on ecosystem management. In particular, there has been a focus on multisectoral conflicts. Driven by EU policy this has especially focussed on better modelling and advice of closed areas (both MPAs and wind farm areas) to better account for the displacement of fishing activity. The talk will also highlight several cases where a lack of political will to agree on choices between conflicting priorities has made progress more difficult. Overall, the science to give better and more relevant ecosystem advice is improving, while challenges remain on translating that into actual ecosystem management.

Keynote #2: Myth, mechanism, and misattribution in Ecosystem-Based Fisheries Management. Matt Robertson, Marine Institute, Memorial University of Newfoundland

Stock assessment models traditionally assumed predictable relationships between fisheries harvest and fish population dynamics. However, fish population dynamics are affected by a variety of ecosystem processes that often invalidate this assumption. Although a variety of approaches now exist to incorporate ecological variation, determining the appropriate level of complexity remains difficult. Here, I will draw on three recent studies to highlight lessons that may be useful for stock assessment scientists hoping to incorporate ecosystem considerations into their models. First, using a simulation study, I will describe how historical assumptions used when modeling environment-recruitment relationships may have biased our perception about the value of these relationships. Second, I will review recent evidence that starvation mortality may represent an overlooked component of natural mortality. Third, I will detail a modeling framework for assessing models across a range of complexity to identify the most likely population and ecosystem processes that affect population dynamics. Together, these examples underscore three principles for ecosystem-informed assessments: 1) modeled truisms about ecology are only true in the context of model assumptions, 2) developing ecosystem-based predictions will require constant re-assessments about which model assumptions are reasonable, and 3) iteratively examining models across a range of model assumptions may provide a useful framework for improving understanding and ensuring that decisions are evidence-based.

Keynote #3: Environmental Information in Stock Assessments of New England Groundfish. Steve Cadrin, University of Massachusetts, Dartmouth

Stock assessment and management of New England groundfish fisheries have been challenged by climate change. As the region rapidly warms, many groundfish stocks fail to rebuild despite precautionary catch limits, and their stock assessments have exhibited diagnostic problems such as severe retrospective patterns. In response to this problem, a collaboration of regional scientists developed an approach to consider environmental information in New England stock assessments. The process involves 1) reviewing information on ecological interactions for each assessed species, 2) testing relationships between environmental indices and population processes (e.g., distribution, recruitment, growth, maturity), and 3) developing stock assessment models with environmental covariates to determine stock status and management advice. The process was applied to relatively data-rich research track assessments American plaice, Atlantic cod, yellowtail flounder, and winter flounder, with iterative progress toward operational application. The most recent yellowtail flounder stock assessments that were accepted for management advice include environmental covariates but demonstrate challenges with catch projections and management reference points. These case studies demonstrate an effective approach to including ecosystem information in stock assessments as well as the need for iterative advancement as the approach is applied more broadly.

salmonMSE: a decision-support tool for Pacific salmon accounting for within-population life-history diversity and environmental drivers (Carrie Holt, Pacific Region)

Risk-based decision support tools are needed for Pacific salmon to inform sustainable management. Like other taxonomic groups, management is expected to account for the biology of the fish and environmental conditions affecting the stock. However, Pacific salmon are unique in several ways resulting in the need for distinct tools. Pacific salmon have high biological diversity, are impacted by environmental conditions in freshwater and marine environments, and their management spans fishery harvest, hatchery enhancement and habitat restoration. salmonMSE is a stochastic, closed-loop simulation tool based on ‘management strategy evaluation’ (MSE) using a life cycle-based model that can incorporate biological realism of salmon populations with harvest, hatchery and habitat management levers. While salmonMSE is a generic tool, it is adaptable to different salmon species, with varying biological characteristics, data availabilities and management contexts. Here, we present a case study on Chinook salmon on the West Coast of Vancouver Island that is exposed to mixed-stock fisheries, and subject to hatchery enhancement and habitat restoration. The model is conditioned on available spawner time-series, hatchery releases, and (coded wire) tagging data, and projections are expanded to include hypotheses about life-history diversity within the populations (early and late maturing fish with different survival rates), and environmental drivers of freshwater survival. In this way management scenarios can be evaluated under various assumptions about the biology of the fish and ecosystem drivers even when data are insufficient to include in the assessment and conditioning model. Future additions to salmonMSE will include a conditioning model that attempts to take the influence of ecosystem conditions on marine mortality (e.g., predators, SST) directly into account.

Time-varying models for Pacific salmon: estimation, model selection and closed-loop simulations (Catarina Wor, Pacific Region)

Time-varying population dynamics in fish populations are becoming increasingly common due to effects of climate change, habitat degradation and other anthropogenic factors. This is particularly true for Pacific salmon stocks which are susceptible to changes in both marine and freshwater environments. In contrast, fisheries reference points are often estimated under the assumption of stationary dynamics, which can lead to science advice that is not sufficiently precautionary or that limits fisheries unnecessarily. However, accurately estimating time-varying dynamics is often difficult, and including time-varying parameters in harvest control rules may not necessarily lead to improved management outcomes. We used a closed-loop simulation approach to evaluate the performance of management strategies given different scenarios of changing spawner-recruit dynamics in Pacific salmon, including changes to the productivity and capacity parameters. We considered harvest control rules based on fixed, stationary and time-varying abundance and removal rate reference points assessed at different frequencies. Our results indicate that there are interactions between the shape of the harvest control rules and the use of different combinations of stationary and time-varying for both abundance and removal reference points. This suggest that the choice of reference points should not be done in isolation but within the context of the harvest control rule and other management strategies being considered.

Incorporation of hydroclimate and exploitation impacts into monitoring, assessment and management of anadromous Dolly Varden population productivity (Xinhua Zhu and Colin Gallagher, Arctic Region)

A warming climate in the western Canadian Arctic has impacted seasonal discharge of rivers, which provides important habitat for anadromous salmonids. Strong seasonal variations in weather and hydroclimate conditions have been identified as an environmental driver impacting the timing of seasonal migrations of anadromous fish populations.

Subsistence fisheries in the western Canadian Arctic rely on stocks of anadromous Arctic Char and Dolly Varden to ensure food security and transmit cultural practices. In response to a decline in the abundance of anadromous Dolly Varden in the Rat River, Northwest Territories, an annual fisheries-dependent community-based monitoring program was initiated in 1995. Experienced Gwich'in harvesters implemented this program to collect fisheries data, including catch-effort and biological information during the upstream migration (late-July to mid-September). Additionally, several qualitative categorical variables pertaining to water level, debris, and water clarity were recorded to track the temporal changes in the environmental conditions and link them to the relative abundance index of migrating Dolly Varden. The assessment of temporal changes in weather and hydrometric indicators may contribute to our better understanding of impacts on the seasonal migration timing and population dynamics, although the qualitative environmental information is difficult to directly apply to quantitative stock assessment.

To incorporate the ecosystem indicators recorded by the harvesters into a stock assessment, our EAFM approach was to i) establish scenario-based causal models linking catch-per-unit-effort of Dolly Varden with the qualitative and quantitative ecosystem indicators, ii) estimate population dynamics parameters using a Bayesian state-space surplus production model, and iii) develop fisheries reference points delineating the historical and current stock status of the population among scenarios. The modelling indicated that the stock is currently in a healthy state. The outcomes will promote an integrated assessment plan for the stock that incorporates environmental considerations.

Modelled reconstructions of marine environmental and ecosystem variables: trends, causal inference, and recent applications in the Pacific Region (Greig Oldford, Pacific Region)

Reconstructions of unobserved environmental and ecosystem variables are increasingly available. Many of these reconstructions include quantification of uncertainty and have been evaluated against the available observational data. An emerging challenge relates to a surplus of potentially relevant time series and covariates. This talk will highlight recent applications of biogeochemical and ecosystem models and causal inference for supporting stock assessments.

Drivers of Pacific Hake recruitment -- lessons learned from trying to operationalize the research (Andrew Edwards, Pacific Region)

Pacific hake (*Merluccius productus*) is a commercially valuable fish species of importance to Canada and the United States. It is assessed and managed bilaterally as a single stock. Published research has determined relevant ecosystem information that appears to influence hake recruitment. Some of the more easily available and updatable information (such as that available in DFO's pacea R package) was amalgamated and presented in the 2025 assesment document, as a first step to developing a reproducible workflow for incorporating some of this information into the model. Lessons learned will be described. The current assessment model does include temperature as an environmental predictor of spatiotemporal maturity-at-age, and uses empirical weight-at-age data. These will be briefly described as examples of including ecosystem information in the age-structured model.

Exploring environmental effects on fish stock recruitment - tools to bolster EAFM and contributions toward CSAS reports (Travis Tai, Pacific Region)

Ecosystem variables can provide valuable insight into biological drivers of fish stock recruitment, yet are not always explicitly included in stock assessments and fisheries management. Here we present methods and resources that streamline the process of integrating environmental analyses in stock assessments. The analyses are introductory and exploratory, assessing each variable separately in a univariate model. It uses readily available ecosystem data from the R package `pacea`, facilitating its use across different species and stock assessments. While this approach is basic, it acts as a foundation for further investigation into specific environmental variables and more complex modelling approaches.

The use of ecosystem variables in 2J3KL Capelin assessments (Aaron Adamack, Newfoundland and Labrador Region)

Capelin is a forage fish species with a circumpolar distribution. They play key roles in multiple sub-Arctic food webs and are considered to be a keystone species in North Atlantic Fisheries

Organization Divisions 2J3KL. The current year's capelin biomass index in 2J3KL is predicted using a modeling suite that is based upon two theories of how capelin biomass is regulated: cohort strength and adult mortality. Two cohort strength models use larval capelin density alone or in combination with zooplankton density to predict the capelin biomass index while two adult mortality models use the timing of sea ice retreat alone or in combination with fall condition of age-1 and -2 capelin. A third set of models combine the different cohort strength and adult mortality models in various combinations resulting in an overall total of 10 forecast models. The environmental variables used in these models reflect the environmental drivers affecting capelin biomass where the cohort strength models are focused around environmental drivers of capelin reproductive success while the adult mortality are focused on drivers that address the ability of capelin to survive harsh winters in the NW Atlantic. The best fitting model uses all 4 variables and has a Bayesian R2 = 0.62.

Linking Prey and Predators: How Capelin Informs the Northern Cod Stock Assessment
(Paul Regular, Newfoundland and Labrador Region)

Northern cod (*Gadus morhua*) off Newfoundland and Labrador collapsed in the early 1990s following decades of heavy fishing and coinciding with major ecosystem change in the Northwest Atlantic. Since then, the stock's slow and uneven recovery has continued to draw attention to the ecosystem processes shaping its productivity. Among the potential drivers – including fishing, temperature, predation, and prey availability – capelin (*Mallotus villosus*) has emerged as a key factor influencing cod condition, recruitment, and survival.

APPENDIX C. BREAKOUT GROUP TOPICS IDENTIFIED PRIOR TO THE WORKSHOP

Prior to the workshop, participants were ask to provide ideas of topics for break-out group discussions and work. While the intention was to identify additional topics during the workshop the following initial set was retained:

When M Isn't Constant: Ecosystem-Driven Mortality and Its Consequences for Management Advice. Host: Paul Regular, DFO Newfoundland and Labrador Region

Natural mortality is dynamic, but we often lack the data or understanding of stock dynamics needed to estimate changes through time. Introducing ecosystem drivers such as prey availability introduces time-varying natural mortality into stock assessments, adding realism but also complexity. Using Northern cod as an example, this breakout will examine how changes in M linked to ecosystem variability, such as shifts in capelin abundance, affect reference points, rebuilding trajectories and perceptions of risk. Discussion will focus on the dual challenge of capturing ecological realism while maintaining clarity and confidence in management advice, and on effective ways to communicate these dynamics to decision-makers and stakeholders.

Incorporating qualitative ecosystem information into stock assessment models. Host: Mackenzie Mazur

Although the literature has primarily focused on the integration of quantitative ecosystem information into single-species stock assessment, incorporating qualitative ecosystem information (i.e. expert knowledge, traditional knowledge) remains a significant challenge. However, for many stocks, especially those that are data-limited, qualitative information may be the only available source of information on ecosystem impacts. This breakout group will explore approaches for incorporating qualitative ecosystem information into assessment models, which could include testing or simulating a range of ecosystem scenarios informed by qualitative input or using qualitative information to inform priors for key parameters. The goal is to brainstorm novel and transparent approaches for incorporating ecosystem impacts in stock assessments when quantitative ecosystem data are limited.

Approaches for considering the spatial and demographic scale of environmental drivers when including those drivers in assessments. Host: Matt Robertson.

The incorporation of ecosystem information into single-species stock assessment models has often focused on the inclusion of a time-series of some environmental covariate to explain temporal variation in some demographic process. However, we know that environmental effects often differ in strength, magnitude, and direction at relatively fine spatial scales and across an animal's ontogeny. The goal of this breakout group will be to discuss approaches for integrating analyses of environmental effects across spatial and demographic scales with stock assessments.

Use of Simulation testing to evaluate impacts of ecosystem changes on Fisheries management Host: Catarina Wor

This topic proposed to examine simulation evaluation of estimation models, and the use of closed loop simulations as well as making cluster computing now available via DFO more accessible. This led to the short session outlined in section 4.4.