WORKING GROUP ON MULTISPECIES ASSESSMENT METHODS (WGSAM)

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Contents

i Executive summary

The Working Group on Multispecies Assessment Methods (WGSAM) aims to advance the operational use of knowledge on predator-prey interactions for advice on fisheries and ecosystem management.

This report summarises the achievements of a 3-year cycle during which the group consolidated criteria to evaluate key-runs and more in general the skills assessment of multispecies models, released key-runs for the Baltic Sea, North Sea and Irish Sea all evaluated with those criteria, progressed in the areas of multiple models comparison, ensemble modelling and on the estimation of biological reference points in the context of multispecies interactions. The updated key-runs for the North Sea and the Baltic Sea provided the best available estimates of predation mortality for a number of key commercial stocks in these two ecoregions which have been already integrated into the stock assessments throughout benchmarks and inter-benchmarks. Analyses accumulate showing that ignoring strong trophic interactions may lead to bias in the perception of stocks status and in the calculation of reference points. Evaluations show advantages of using multi-model ensembles to capture the dynamics of the main stocks and the system overall. Results accumulated so far suggest that the benefits of ensemble modelling exist for both simple models, i.e. multispecies production models, as well as more complex ecosystem models. Various approaches are available to the practice of ensemble modelling, including a fully Bayesian ensemble framework suitable also for multi-model forecasts.

The report includes also progresses with software developments to enhance accessibility of some complex routines, including ensemble modelling beyond "just a simple average approach" and computation of multispecies reference points, to a broader group of modellers and users. The group sees these developments as a great opportunity to work more towards cross-platform comparisons and further on multispecies skill assessment which will remain important themes for continuation of the work. To further progress the use of multispecies and ecosystem models, collection of ecosystem data remains highly relevant, with priority on stomach data and other information on processes affecting trophic interactions and trophodynamics of ecosystems (i.e., predator-prey overlap, temperature-dependent consumption, availability of other food).

ii Expert group information

Expert group name	Working Group on Multispecies Assessment Methods (WGSAM)
Expert group cycle	Multiannual
Year cycle started	2019
Reporting year in cycle	3/3
Chairs	Sarah Gaichas, USA
	Valerio Bartolino, Sweden
Meeting venue(s) and dates	14–18 October 2019, Rome, Italy, 19 participants
	12–16 October 2020, online, 24 participants
	11–15 October 2021, online, 34 participants

1 List of terms of reference (ToR)

ToR A. Regional updates: Review further progress and deliver key updates on multispecies modelling and ecosystem data analysis contributing to modelling throughout the ICES region.

ToR B. Key-runs: Update of key-runs (standardized model runs updated with recent data) of multispecies and ecosystem models for different ICES regions.

ToR C. Skill assessment: Establish and apply methods to assess the skill of multispecies models intended for operational advice.

ToR D. Multi-model advice: Evaluate methods for generating advice by comparing and/or combining multiple models.

ToR E. MSE: Management Strategy Evaluation (MSE) methods and applications for multispecies and ecosystem advice, including evaluating management procedures and estimating biological reference points.

2 Summary of achievements during 2019–2021

- Keyruns: Modelling output and advisory products
  - SMS NS (see report 2020)
  - SMS Baltic (see report 2019)
  - EwE Irish Sea (see report 2019)
- M values from SMS keyruns were used in the assessments of stocks in:
  - North Sea cod (cod.27.47d20), haddock (had-34), whiting (whg.27.47d), herring (her.27.3a47d), sprat (spr.27.3a4) and sandeel (san.sa.1r, san.sa.3r)
  - Baltic Sea herring (her-2532-gor) and sprat (spr-2232)
- The EwE Irish Sea model has been adopted in the ICES WKIRISH to produce synthesised ecosystem indicators
- Methodological developments
  - Established keyrun review criteria (see reports 2019–2020)
  - Consolidate platforms for skill assessment and advance methods for testing parameter sensitivity in complex models
  - Ensemble modelling is tested in several applications primarily from the North Sea
  - More efficient algorithms open the door for application of the Nash equilibrium in contexts such as MSE and sensitivity analyses where computational efficiency has represented a limit in the past
- Software and libraries
  - *atlantisom* R package for the use of Atlantis as operating model (ToR c)
  - routine for model ensemble in Rpath (see ToR d)
  - routine for MSE in Rpath (see ToR e)
  - *nash* R package for calculation of Nash equilibrium (upcoming R package, see ToR e)
  - library for Bayesian ensemble modelling (upcoming R package, see ToR d)
- Papers associated to WGSAM activities are reported in the section "Relevant papers" under each ToR.

3 Final report on ToRs

3.1 ToR A. Review further progress and deliver key updates on multispecies modelling and ecosystem data analysis contributing to modelling throughout the ICES region

Over the course of 2019–2021, WGSAM received updates on modelling in the following regions: North Sea, Irish Sea, Celtic Sea, US northwest Atlantic Shelf, Baltic Sea, west of Scotland, Gulf of Alaska, Gulf of Maine, English Channel, Kattegat, and the Portuguese shelf. Summaries of the models presented are available in Annex 3.

Notable key points of the progress of multispecies and ecosystem modelling throughout the ICES regions are:

1. The number of multispecies and ecosystem models developed in connection with WGSAM has continuously grown, including models that undergone in depth reviews as keyruns and which are being maintained and regularly updated. In several regions we have now multiple models (e.g., Ecopath with Ecosim, Gadget, SMS, and others.) built on the same ecosystems which is supporting other ToRs and contributing to: (i) improve our understanding of the different modelling frameworks, (ii) build confidence on the outcomes of multispecies and ecosystem models (iii) better characterise uncertainties.
2. There is an increase in models including the impact of temperature (or other environmental drivers) which are being used to assess the impact of climate change on marine ecosystems.
3. There is also increased consideration for the human dimension in models in order to enable integrated ecosystem assessment (e.g., Baltic Sea).
4. Effort is being made to make model outputs better suited to inform managers, for instance by exploring trade-offs between all possible yield combinations from a complex of interactive species. The convex-hull of this set plotted on the x-y plane in a pairwise manner results in Pareto frontiers within which any management objective is possible. What is not possible is attaining single-species MSY values which ultimately result in points that are not enclosed by these frontiers. Multispecies MSY reference points in the sense of a Nash equilibrium with respect to fishing mortality rates provides a point within these areas for all pairwise combinations. This form of Nash equilibrium MSY is conceptually the most intuitive translation of single-species MSY given the existing European management framework.
5. Relating to point 1), there is an increase in the use of ensemble models to provide better estimates. Ensemble models are considered to be more reliable than a single model.
6. In some cases, some models are transitioning into an easier to use, more transparent framework, i.e., R packages. Notable examples of this include Rpath to create Ecopath with Ecosim models, LeMaRns to create LeMans models, and Rgadget for gadget models.

Relevant papers

Kulatska N., Woods P., Elvarsson B., Bartolino V. 2021. Size-selective competition between cod and pelagic fisheries for prey, ICES J. Mar. Sci. 78: 1872-1886, https://doi.org/10.1093/icesjms/fsab094

Szalaj, D., Torres, M.A., Veiga-Malta, T., Angélico, M.M., Sobrinho-Gonçalves, L., Chaves, C., Alcoforado, B., Garrido, S., Ré, P., Cabral, H., Silva, A., 2021a. Food-web dynamics in the Portuguese continental shelf ecosystem between 1986 and 2017: Unravelling drivers of sardine decline. Estuar. Coast. Shelf Sci. 251, https://doi.org/10.1016/j.ecss.2021.107259

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Spence, M. A., Bannister H. J., Ball J. E., Dolder P.J. Griffiths C.A. and Thorpe R.B., 2020, LeMaRns: a Length-based Multi-species analysis by numerical simulation in R, PlosOne, 15(2),e0227767.

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Spence, M. A., Blanchard, J. L., Scott, F., Thorpe, R. B. and Blackwell, P. G, 2021, Quantifying uncertainty and dynamical changes in multi-species fishing mortality rates, catches and biomass by combining state-space and size-based multi-species models, Fish and Fisheries, 22(4), 667–681.

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Veiga-Malta, T., Szalaj, D., Angélico, M.M., Azevedo, M., Farias, I., Garrido, S., Lourenço, S., Marçalo, A., Marques, V., Moreno, A., Oliveira, P.B., Paiva, V.H., Prista, N., Silva, C., Sobrinho-Gonçalves, L., Vingada, J., Silva, A., 2018, First representation of the trophic structure and functioning of the Portuguese continental shelf ecosystem: insights into the role of sardine, Mar. Ecol. Prog. Ser. https://doi.org/10.3354/meps12724

3.2 ToR B. Key-runs: Update of key-runs (standardized model runs updated with recent data) of multispecies and ecosystem models for different ICES regions

WGSAM Term of Reference b) for 2019–2021 reads:

Update of key-runs (standardized model runs updated with recent data, producing agreed output and agreed upon by WGSAM participants) of multispecies and ecosystem models for different ICES regions. The key-runs provide information on natural mortality for inclusion in various single species assessments. Deliverables: Report on output of multispecies models including stock biomass and numbers and natural mortalities for use by single species assessment groups and external users.

To address this ToR, WGSAM developed a set of model review criteria[1] and applied them to four multispecies model key-runs in 2019–2021: Baltic Sea SMS, Baltic Sea Gadget, Irish Sea EwE, and North Sea SMS. Reports from these model key-run reviews (ICES 2019, 2021) supported advice processes in the Baltic Sea (WGBFAS), Irish Sea (WKIRISH), and North Sea (HAWG, WGNSSK). We briefly summarise the criteria and review results here, then discuss future approaches for WGSAM key-run reviews.

[1] https://ices-eg.github.io/wg_WGSAM/ReviewCriteria.html

Multispecies Model Review Criteria

WGSAM applies key-run review standards developed for reviewing models used in environmental and regulatory decision making, which differ from purely academic models. The general standards are outlined in (NRC 2007) and applied by ICES WGSAM (ICES 2019, 2021). There are three key attributes of "good" models spanning the range from stock specific through multispecies up to ecosystem models intended for supporting decision making: (i) they are based on generally accepted science and methods, (ii) they serve the intended purpose, and (iii) they behave similarly to the actual system. Review criteria are derived from these three attributes, and are modified for different phases of the model life cycle, from problem identification to conceptual model and constructed model, through model use. Different phases of the model life cycle align with different evaluation issues. Here, we outline six general review criteria developed and applied by WGSAM 2019–2021. These review criteria were also presented as multispecies modelling best practices at a multispecies modelling workshop in June 2021 (Karp *et al.* 2021), where a version of this text was also contributed by S. Gaichas.

The first criterion relates to problem identification, where early in the model life cycle we critically evaluate our objectives and why we need a model at all. WGSAM generally establishes that the problem is clear, and then determines whether the model is appropriate for the problem. For multispecies and ecosystem models, it is important to clearly specify the need for models of this level of complexity, and the key output(s) of interest.

The second criterion evaluates whether the scientific basis of the model is sound and appropriate for the problem. This applies to model framework and constructed model phases of the life cycle, but is also important for model use. WGSAM generally follows the NRC criteria for soundness and has also used basic performance criteria outlined in (Kaplan *et al.* 2016) for general soundness of complex ecosystem models.

The third criterion evaluates whether input data quality and parameterization are adequate for the problem. WGSAM suggests best practice to facilitate review is for modellers to provide summary charts of data showing which types are available and used, time-series length, gaps, and species comparisons across species. Data pedigree and uncertainty measures should also be provided. Assumptions behind modelled ecological, biological, and other processes must be clearly stated and appropriate, and basic diagnostics of model inputs/outputs evaluated for ecological soundness.

The fourth review criterion is where we spend much of our time in evaluating stock assessment models. How does model output compare with observations? Best practices for comparing model output with observations include the usual evaluation done for stock assessment models of fits to surveys, catches, composition data, etc. However, there are other equally important considerations. Clear definition of the hindcast period, key species/groups/indicators, spatial patterns, and outputs of interest that are most critical to addressing the problem ensures that the model is working well enough, but not setting up unrealistic expectations to fit everything. WGSAM notes that fitting data well does not imply predictive ability! Fit diagnostics are not the same as skill assessment against a known dataset.

The fifth review criterion addresses model uncertainty and sensitivity. Has uncertainty been estimated in the output(s) of interest for the problem? Has sensitivity to key datasets and parameters been assessed? Model analyses should include retrospective analysis, forecast uncertainty (if forecast necessary for the problem), and it is recommended to retain multiple parameterizations of a model that all meet performance criteria to bracket parameter uncertainty in model applications.

WGSAM also reviews previous model peer reviews to evaluate model performance over time and whether suggested revisions have been incorporated. Peer review is most effective at each stage of model life cycle. In addition, peer review within a management process in association with a policy problem is a best practice to ensure that the model is most effective and likely to be used. Iterative feedback between modellers, managers, and stakeholders has been shown to be effective in building models useful to management (Townsend *et al.* 2019; Bentley *et al.* 2021).

Key-run review summaries

Baltic Sea SMS and Gadget

For the Baltic Sea, multispecies model key-runs estimate predation mortality to provide time-series of natural mortality (M) for use in single species stock assessments for herring and sprat. Therefore, the review of key-runs from an SMS model (used in the previous 2012 key-run) and from a newly developed Gadget model focused on the ability of the models to provide M time-series for these species. Overall, both models provided consistent time-series of M for herring and sprat when using the same assumptions regarding residual natural mortality, despite different representations of cod population dynamics. However, due to issues of stability in the historical part (prior 1990s), the Gadget model was not selected as a key-run.

WGSAM recommended the use of natural mortality estimates from the Baltic SMS key-run for use in single species stock assessment models of Baltic herring and sprat. While SMS results have shown some sensitivities to e.g., consumption rates, assumptions regarding the residual mortality M1 as well as the size selectivity of cod, the very similar results from the Gadget model run and the absence of retrospective patterns are encouraging and increase the credibility of the M time-series estimated by WGSAM. Worth to note that the results of the SMS key-run depend to a large extent on the outcome of the ICES Eastern Baltic cod assessment. Any bias in this assessment directly influences the predation mortality estimates. WGSAM did not recommend use of the uncertainty estimates around M estimated by SMS as these are underestimated due to the assumption that the cod population is known without error.

Irish Sea EwE

For the Irish Sea, the ICES WKIRISH requested review of an Irish Sea Ecopath with Ecosim (EwE) model. An aim of the WKIRISH process is to suggest methods by which some of the outputs of the Irish Sea EwE can be used to influence quota setting. The aim of WKIRISH is not to use F values directly from the EwE, but rather to use the EwE output as a synthesized ecosystem indicator to help inform the choice of Ftarget within the pre-defined Fmsy ranges. This method would allow for the incorporation of ecosystem information within the quota setting process, while remaining within the existing precautionary fisheries management framework and the current reference point ranges used by ICES.

WGSAM approved the Irish Sea EwE model as a key-run to provide a basis for producing indicator(s) which could be used to inform the selection of fishing mortality targets within a pre-defined range of F values evaluated as precautionary using the single species assessment models. WGSAM did not recommend directly transferring Fmsy values estimated by the EwE model into other models or for direct use in management.

North Sea SMS

WGSAM recommended the use of natural mortality estimates from the North Sea SMS key-run for use in single species stock assessment models of North Sea cod, haddock, herring, Norway pout, southern North Sea sandeel, northern North Sea sandeel, sprat, and whiting.

WGSAM accepted the model output from SMS as key-run with the settings given in the Stock Annex. WGSAM considers the key-run as currently best possible run with SMS to provide natural mortality estimates. WGSAM recommends using these values as input to single species stock assessments. The full time-series should be used and not only an update for the years after the last key-run in 2017.

For further work WGSAM recommended the following:

1. There is a need for updated stomach sampling to understand how diets have changed with changes in species ranges. There are large proportions of other food in the diets of several species. Ideally, these need to be refined and it needs to be assessed whether this has changed.
2. Need for better knowledge of the proportion of several stocks (hake, mackerel, North horse mackerel) that habituate the North Sea.
3. A future run with age 1 as recruits could be tried because the input for the 0 group is highly uncertain for many species.
4. Need of further investigations related to the following issues: • No size preference in predation is implemented in the model at the moment. With more stomach data it would be possible to test the impact of such an assumption • Unclear why the M2 CV increases for a number of prey stocks • Impact of the Dirichlet estimated parameter on the resulting predation mortality in general, and reason behind the need of a scaling factor for the hake Dirichlet parameter

Future of key-run reviews

WGSAM discussed the need to balance requests for reviews of new model key-runs that represent potential scientific modelling advances versus operational model key-runs limited to data updates but are otherwise previously reviewed in the model structures and routines. The former advance science, while the latter support a fundamental component of EBFM within ICES as single species assessment inputs capturing key ecosystem processes.

WGSAM intends to balance these needs by continuing to select a key-run for review within the annual working group meeting that represents a new model and/or scientific advance and is feasible to review alongside work on other WGSAM ToRs. For operational model key-runs that have been previously reviewed and are needed for stock assessment inputs, WGSAM discussed reviews outside the annual working group meeting with a subgroup of reviewers who ideally would also include single species stock assessment experts and ecosystem experts within the key-run region. This would align the operational key-run with the timing and needs within the region and also better coordinate common data inputs needed by the multispecies model and single species models in the region. Finally, WGSAM may schedule more in-depth reviews for complex multi-model key-runs during special workshops dedicated to that task alone. For example, a key-run in progress for Georges Bank (USA) will include a multispecies surplus production model, a length structured multispecies model, an age structured multispecies model, and a foodweb model, all fitted to a common dataset. Adequate review of this suite of models will likely require several days in a separate workshop with WGSAM members. This workshop would also allow inclusion of experts outside WGSAM.

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Relevant papers

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3.3 ToR C. Skill assessment: Establish and apply methods to assess the skill of multispecies models intended for operational advice

Approaches focusing on different aspects of skill assessments for multispecies and ecosystem models were presented during the meetings of WGSAM in 2019, 2020 and 2021. A wide range of topics was presented, from testing the performance of multispecies models and assessing their uncertainty to developing datasets that can be used in skill assessment. Summaries of all presentations can be found in Annex 4 of this report.

Some of the main outcomes of the contributions presented in the last 3 years are as follows:

- Methods for sensitivity analysis (SA) and uncertainty analysis (UA) make up an important part of the contributions of ToR C. Over the last three years, several new methods have been developed and tested. For example, to allow testing model sensitivity to variations in multiple parameters simultaneously: the implementation of Morris SA in an Atlantis model. Also, to decrease the simulation time of UA of multispecies models and model ensembles: the development of Gaussian process emulators that discount implausible regions of the parameter space given the observed data. In addition, to test the effect of variability in initial conditions: initial conditions UA were developed for an Atlantis model.

- Model uncertainty can be expressed as a utility factor, which expresses the cost efficiency of reducing the model uncertainty. Model utility is a useful indicator in the management decision-making process. Model utility can be used for ensemble models, where different indicators for goodness of fit, such as accuracy, precision and correlation together define the model utility.
- A second important part of the contributions considers improving the representation of the population and foodweb interactions in multispecies fisheries models. Understanding the grey area of foodweb modelling could improve future projections or reference points. For example, a state-space multispecies model has shown that ignoring trophic interactions can induce bias in stock perception and reference point estimates. This occurs because models that ignore predation have reduced predictive ability despite a fit to the observations that can appear good. Also, to work around the data vacuum in fisheries data of small sized individuals, a mizer model was used to simulate recruitment at smaller sizes (sub age-0 classes), which led to recruitment estimates quite different from the ICES recruitment estimates. The estimation of reference points can benefit from improving the mechanics at young and old age by tuning the model to biomasses from assessments of assessed stocks.
- A novel topic in skill assessment is the impact of climate change on model performance. Simulations with Atlantis models, configured for the California Current and Nordic/Barents Seas, tested the effect of different climate scenarios on model performance.
- Different approaches using a multi-run strategy were able to fit models better than single run fitting, both in case of simple and more complex foodweb models. A development of multi-language scripts and GUI allowed use of multiple estimation algorithms and objective functions for evaluation of models' skills.

Since 2018, a collaboration among members of WGSAM has started on writing a best practice paper for skill assessment of multispecies models that can be applied in ICES, particularly when reviewing key runs as well as in other fishing communities when reviewing multispecies models. The progress on the manuscript was presented every year at the WGSAM meetings. This year the manuscript is close to completion and should be submitted in the upcoming months.

Numerous efforts have been made in the past years to standardize the way the key runs are performed, reviewed and results are stored as key runs are a core activity of WGSAM. While best skill assessment practices/criteria were developed in WGSAM, they were applied when reviewing the different key runs.

In addition, in 2019, a skill assessment project started to emerge after a R-package (atlantisom[1]) that creates datasets for skill assessment from Atlantis model outputs was presented at the 2019 WGSAM meeting. It was then decided to work on a collaborative project within WGSAM to use this dataset as observations for the different multispecies estimation models used by the WGSAM members. Much progress has been made since then with regular interim meetings between WGSAM members. Preparing the dataset for the different multispecies models is close to completion and will be soon sent to the different modellers to start the fitting procedure.

In conclusion, skill assessment of multispecies models is still a work in progress in WGSAM. More work is needed to finalize the skill assessment paper and project, and investigate calibration and validation of multispecies models. Therefore, it is recommended to continue this ToR in the next three years under the same name.

Relevant papers and package

https://github.com/r4atlantis/atlantisom

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3.4 ToR D. Multi-model advice: Evaluate methods for generating advice by comparing and/or combining multiple models

Tools and applications of multi model ensembles were presented during WGSAM 2019, 2020 and 2021. At the WGSAM 2017, a number of multi model ensembles were being developed to synthesize and combine outputs of one or several multispecies models while providing a full picture of underlying uncertainties. The presentations at the recent WGSAM meetings, from 2019 to 2021, highlighted much progress that has been made towards making these approaches operational for providing multispecies advice and supporting ecosystem-based fisheries management. One approach, the ensemble modelling framework, summarizes the outputs of multiple models exploring various fisheries management scenarios to identify their implications for the ecosystem status, stocks and identify multispecies reference points. Its application is now facilitated by a new upcoming R package which implements the fully Bayesian model ensemble framework presented by Spence *et al.* (2018).

A second approach, Rpath, proved to be useful for comparing ecosystem models (quantitative and/or qualitative) while also aiding the formatting of models (e.g., EwE) and their connection to the previously mentioned ensemble modelling framework.

Finally, the provision of multispecies/ecosystem models to ICES regional WK such as the WKIRISH confirms that they are now recognized as key tools for multispecies advice and that, with the help of the recent developments presented at the last WGSAM meetings, multi-model approaches will find their place in fisheries advice.

Previous work presented at WGSAM in 2019 and 2020 provided a foundation for model ensembles and advice discussed in 2021. Key points spanning 2019–2021 can be found in the Annex 5.

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3.5 ToR E. MSE: Management Strategy Evaluation (MSE) methods and applications for multispecies and ecosystem advice, including evaluating management procedures and estimating biological reference points

Ecological interactions are amongst those “biological complications” of the MSY concept. The issue of multispecies MSY (MMSY) has been known for decades (Pope 1976, Larkin 1977, May *et al.* 1979).

In the real world, MSY of a stock is a function of the fishing mortalities on all the other stocks interacting with it, making definition and application of MSY to each stock individually unsuitable as a guiding principle. For instance, in a predator-prey system maximising the yield of the predator requires its prey to be unexploited, whereas by harvesting the predator the yield of the prey can be maximised. The MSY objective “is only as valid as the underlying model” used to describe the fishery (Sissenwine 1978). Therefore, an oversimplified representation of reality (i.e. single-species modelling) translates into an unattainable MSY objective.

Once the operating model explicitly acknowledges the system's trophic structure, there is no unique avenue to translate the single-species MSY objective to a multispecies (MS) analogue (Farcas & Rossberg 2016). Conceptually, the idea of "maximising the yield from each stock separately" in the sense of a Nash equilibrium (Nash 1951) with respect to fishing mortalities is perhaps the closest MS analogue based on the existing European framework. Several authors have proved the existence of such a solution for the Baltic Sea and North Sea ecosystems using different models (Norrström *et al.* 2017, Thorpe *et al.* 2017, Thorpe & De Oliveira 2019, Thorpe 2019 and Spence *et al.* 2020).

Advances of multispecies modelling in the context of fisheries advice has stimulated a new discussion which has also benefit by the increasing interest and use of management strategy evaluation approaches (MSE and MSE-like). The complexity of multispecies models, their ability to represent ecosystems components beyond the exploited stocks, and the different implementation that they offer of ecological processes, especially of end-to-end models, in comparison to stock assessment models, make them ideal tools for the development of operating models. However, these advantages come at the expenses of complexity in the implementation within MSE. Several contributions have been presented during this 3-years cycle for which the main outcomes are summarised below:

- Advances with the software Rpath https://noaa-edab.github.io/Rpath/ (Lucey *et al.* 2020) were presented for its use as an operating model. The model can simulate surveys with observation error and fishery catch that can be used within an MSE framework to feed an assessment model and test alternative management strategies by including the feedback loop of management.
- Like for the single species MSY, also MMSY is sensitive to the model used. Together with other sources of uncertainty, this structural uncertainty can be rigorously captured with the use of multiple multispecies models and Bayesian approaches into an ensemble of MMSY or Nash equilibria.
- The R package "nash" (Del Santo O'Neill *et al.* 2021) has been developed to facilitate the computation of Nash equilibrium MSY reference points for any abstract ecosystem model through a novel efficient algorithm. The superior performance of nash's algorithm over round-robin-like routines previously utilised in this context eases the computational burden when performing sensitivity analyses, management strategy evaluations, or when exploring model variants where many Nash equilibria need to be calculated. Ultimately, nash enhances the use of multispecies models for fishery advice. The package is expected to be released on CRAN and can be downloaded from https://github.com/ThomasDelSantoONeill/nash.
- To facilitate the advisory and/or comprehension of multispecies model outputs, a convenient visualisation was introduced by Beddington & May (1980) where all possible yield combinations amongst all harvested species are plotted in a pair-wise manner. The convex hull of these sets results in Pareto frontiers within which any management objective is possible (*e.g.* Nash equilibrium MSY policies). The shape of these areas varies between right triangles ("complete competition") and rectangles ("no interactions"). SS-MSY values result in the upper-most-right vertex of these rectangles. A synthetic metric can then be derived to pinpoint the part of the complex that requires a MS approach to management if attainable objectives are desired. Different operating models might produce different shapes of these frontiers, but they can be easily compared visually, assess trade-offs and generate plausible targets in the real MS world.
- Using an ecosystem based estimate of M closer to reality contributes to providing better estimates of stock status, reduces the risk of collapse and increases the yield, but specially

optimizes the relation between risk of collapse and annual yield, in comparison to using other options like constant M by age over time or life-history based vectors of M. The benefits of using ecosystem based M values are increased when this approach is implemented for all the commercial stocks at the same time.

- Development of integrated risk metrics that evaluate a "community risk" which is not just the average of the risk across all stocks. This is needed because a) a simple average combined with a 5% level of precautionarity would permit the extinction of stocks if there were more than 20 in a community, and b) trade-off of individual stock risks against each other requires some level of stakeholder input (see Thorpe and De Oliveira, 2019).

MSE could be a route by which multispecies models can impact on the advisory process by allowing them to shape management plans, without having to amend the existing single species process.

The idea of "maximising the yield from each species separately" so ubiquitously spread in legislation takes the form of a Nash Equilibrium (NE). As a result, NE-MSY continues to be the best analogue of SS-MSY in real world fisheries management. However, calculation of NE-MSY via simple brute-force algorithms might be impractical in the computational sense and strongly dependent upon the operating model utilise to emulate reality. The R package "nash" streamlines the computation of NE reference points for any abstract user-defined multispecies model.

Pareto frontiers have the potential to facilitate the identification between plausible and inviable management targets. Furthermore, their shapes provide a visual tool to identify, where in a complex of interacting species, true MS advice is needed if realistic sustainable targets are to be issued. Finally, it eases the comparability between targets computed using different operating models.

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WGSAM 2019 meeting

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Annex 2: WGSAM Resolution

The **Working Group on Multispecies Assessment Methods** (WGSAM), chaired by Sarah Gaichas, USA, and Valerio Bartolino, Sweden, will work on ToRs and generate deliverables as listed in the Table below.

	Meeting dates	Venue	Reporting details	Comments (change in Chair, etc.)
Year 2019	14–18 October	Rome, Italy		
Year 2020	12–16 October	online meeting/ by corresp.		physical meeting cancelled - remote work
Year 2021	11–15 October	online meeting	Final report by 1 December to SCICOM	**Change in Chair** Incoming co-chair: Valerio Bartolino Outgoin co-chair: Alexander Kempf

ToR descriptors

ToR	Description	Background	Science Plan codes	Duration	Expected Deliverables
a	Review further progress and deliver key updates on multispecies modelling and ecosystem data analysis contributing to modelling throughout the ICES region	This ToR acts to increase the speed of communication of new results across the ICES area	5.1; 5.2; 6.1,	3 years	Report on further progress and key updates.
b	Update of key-runs (standardized model runs updated with recent data) of multispecies and eco-system models for different ICES regions	The key runs provide information on natural mortality for inclusion in various single species assessments	5.1; 5.2; 6.1	3 years	Report on output of multispecies models including stock biomass and numbers and natural mortalities for use by single species assessment groups and external users.
c	Establish and apply methods to assess the skill of multispecies models intended for operational advice	This work is aimed at assessing the performance of models intended for strategic or tactical management advice.	5.1; 6.1; 6.3	Establish methods 2019, apply 2020-2021	Manuscript for methods, report on success of methods for different examples.
d	Evaluate methods for generating advice by comparing and/or combining multiple models	This work is aimed at addressing structural uncertainty in advice arising from multiple models, as applied for example management questions	5.1; 6.1; 6.3	3 years	Report on methods for comparing models and for constructing model ensembles.
e	Management Strategy Evaluation (MSE) methods	Adapting existing multispecies/ecosystem	5.3; 6.1; 6.3	3 years	Review of MSE modelling approaches.

	and applications for mutispecies and ecosystem advice, including evaluating management procedures and estimating biological reference points	models for MSE (operating models, assessment models), visualizing tradeoffs and uncertainty for managers and stakeholders		Review of visualization methods. Review of applications throughought the ICES area with lessons learned.

Summary of the Work Plan

Year 1	All ToRs, Key run Baltic, multiple models
Year 2	All ToRs, Key Run North Sea SMS (maybe others)
Year 3	All ToRs, Key Run US Northeast Shelf, multiple models

Supporting information

Priority	The current activities of this Group will lead ICES into issues related to the ecosystem effects of fisheries, especially with regard to the application of the MSY Approach. The activities will provide information (e.g., natural mortality estimates, performance of indicators) and tools (e.g., multi-model ensembles, keyrun models) valuable for the implementation of an integrated advice in several North Atlantic ecosystems. Consequently, these activities are considered to have a very high priority.
Resource requirements	The research programmes which provide the main input to this group are already underway, and resources are already committed. The additional resource required to undertake additional activities in the framework of this group is negligible.
Participants	Approx 20. Expertise in ecosystem, modelling and fish stock assessment from across the whole ICES region.
Secretariat facilities	None.
Financial	No financial implications.
Linkages to ACOM and groups under ACOM	ACOM, most assessment Expert Groups
Linkages to other committees or groups	WGMIXFISH, WGDIM, WGBIFS, IBTSWG, WGECO, WGINOSE, WGIAB, WGNARS, WGIPEM.
Linkages to other organizations	None

Annex 3: ToR A

Review further progress and deliver key updates on multispecies modelling and ecosystem data analysis contributing to modelling throughout the ICES region

The review of progress of multispecies models in ICES Ecoregions given below is not intended to be comprehensive and exhaustive. It reflects the knowledge available to the participants at the 2021 meeting and input from WGSAM who were not able to attend in person.

Ecoregion A. Arctic Ocean

No update

Ecoregion B. Greenland Sea

No update

Ecoregion C. Norwegian Sea

No update

Ecoregion D. Barents Sea

No update

Ecoregion E. Icelandic Waters

No update

Ecoregion F. Faroes

No update

Ecoregion G. Celtic Seas

Ecosystem modelling as a long-term planning tool: identifying sustainable fishing regimes for the west Scotland demersal fishery under future warming (contributed by Alan Baudron, Natalia Serpetti, Aurore Ponchon, Niall Fallon, Paul Fernandes)

In the last 30 years, sea temperatures have risen throughout the northeast Atlantic shelf where most of the northern European fisheries operate, including in the west of Scotland (González-Pola *et al.* 2018). Warming-induced changes in species composition and the resulting changes in trophic foodweb interactions can have large scale impacts on marine ecosystems. These changes are likely to affect commercial fisheries depending on these ecosystems, thereby challenging the future sustainable exploitation of marine fish stocks. In Europe, fisheries management advice is largely based on single-species models delivering short-term forecasts. However, multi-species and ecosystem models which account for trophic interactions are being explored to produce long-term forecasts.

Here, we used the foodweb ecosystem model Ecopath with Ecosim adapted by Serpetti *et al.* (2017) to perform simulations of the west of Scotland ecosystem under future warming in order to identify sustainable and profitable fishing regimes for the west of Scotland demersal fishery. The model includes both species-specific optimum temperatures and the thermal ranges. The west of Scotland demersal fishery exploits the boreal species cod (*Gadus morhua*) and haddock (Melanogrammus aeglefinus), the temperate species saithe (Pollachius virens), and the lusitanian species whiting (*Merlangius merlangus*) and hake (*Merluccius merluccius*). Currently both stocks of cod and whiting are very depleted. In contrast, the biomass of saithe and hake has increased in recent years. We performed forward simulations with two alternative warming scenarios based on medium (IPCC 4.5) and severe (IPCC 8.5) greenhouse gas concentration trajectories defined by the Intergovernmental Panel on Climate Change. For each scenario, we explored different combinations of fishing mortalities applied to each of the five species of the demersal fishery in order to identify: (i) fishing scenarios which would recover the stocks of cod and whiting and (ii) scenarios which would maximise the catch of the demersal fishery whilst achieving sustainable exploitation.

In terms of biomass, it was possible to achieve recovery of both cod and whiting under IPCC 4.5 and IPCC 8.5. However, in both cases cod required a substantial reduction in F from F status quo and below that of MSY, while whiting with its higher temperature optimum was able to sustain higher Fs under a warming environment. Under IPCC 4.5, cod was able to sustain F=0.1, and its recovery and resulting predation prevented whiting to recover above Bpa, although it came close to it. Under IPCC 8.5 however, cod required a complete absence of fishing on the long term, indicating that the eventual recovery under high climate would be under jeopardy in case of any increase in mortality, fishing related or otherwise. Other demersal stocks, hake and saithe, were able to sustain higher fishing mortalities with their biomass declining to a level on par with the late 1990s. However, results indicate that saithe, with its thermal optimum considerably lower than hake, would not be as resilient under a warming environment.

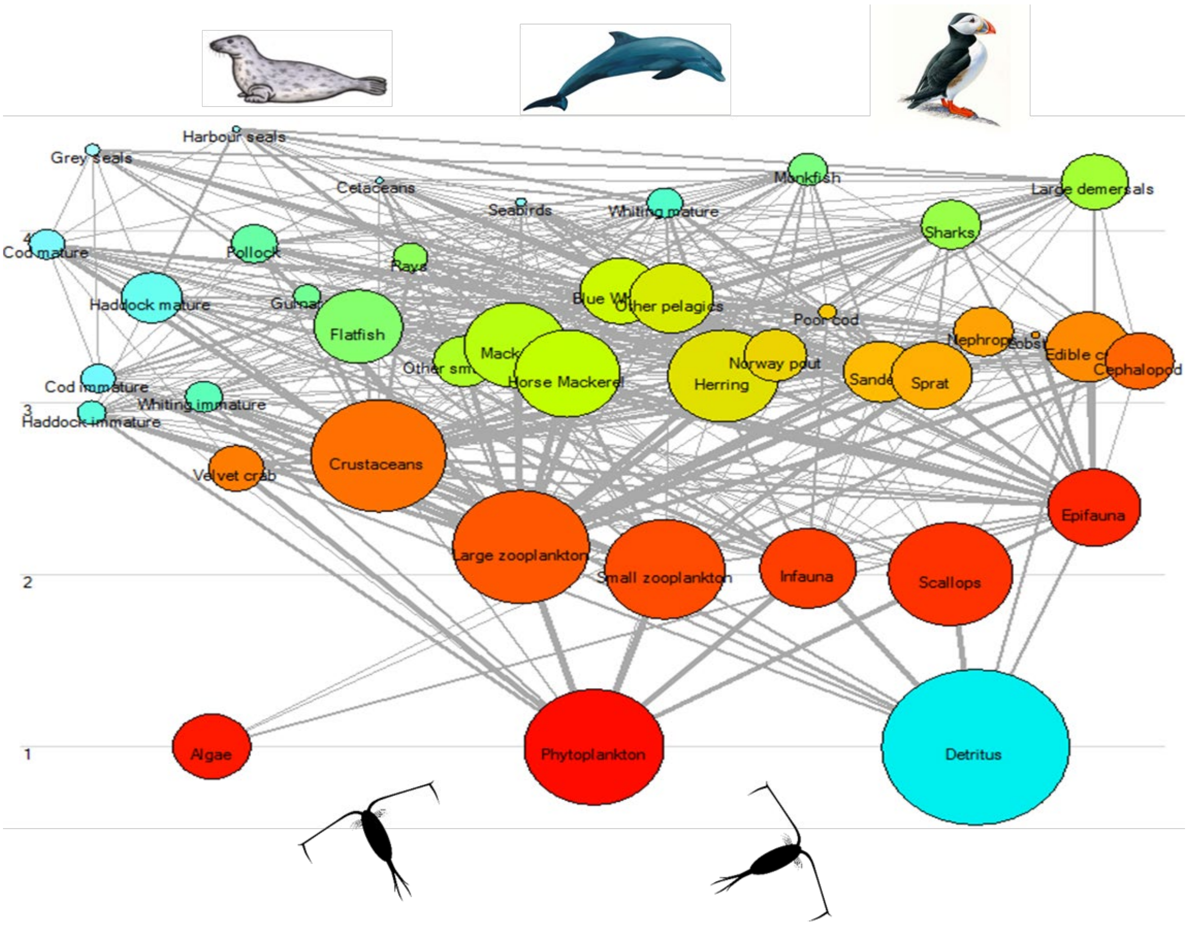
In terms of production, landings achieved for emerging demersal species under IPCC 8.5 were considerably higher than for IPCC 4.5, as detailed in Table 1 below.

Table 1. Cumulative landings achieved with the best management scenario identified (each scenario identified separately and thus corresponding to a different set of Fs). The last column corresponds to the difference between IPCC 8.5 and IPCC 4.5 (4.5 subtracted to 8.5).

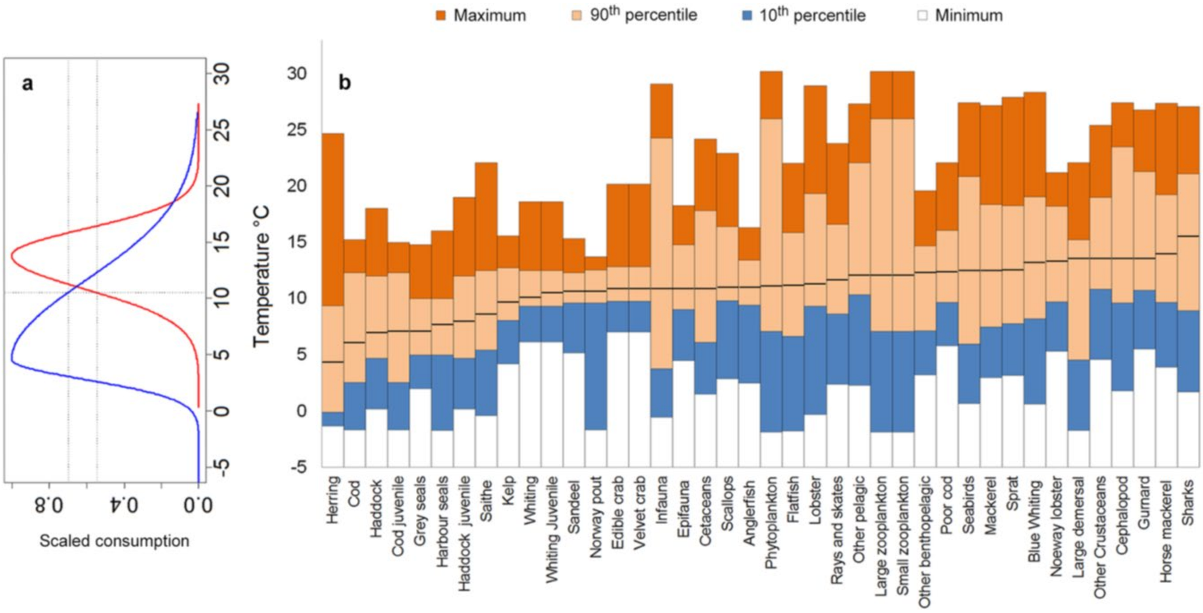
Cumulative landings 2014 to 2050 (tonnes)	**IPCC 4.5**	**IPCC 8.5**	**IPCC 8.5 - IPCC 4.5**
Hake, saithe, monk-fish	4293640	4592229	298589
Whiting	362820	493423	130603
Hake, saithe, monk-fish, whiting	4554529	4991101	436572

This suggest that it would be possible to achieve higher production by increasing exploitation on species which are performing well under warming, hake and whiting in particular. However, the figures given here are subject to the scenarios depicted here being applicable in practice which may well not be the case.

Lastly, regarding ecosystem effects and interactions, the results highlight the importance of considering predator prey interactions. In particular, it may be possible to maintain cold water species (e.g., cod) at sustainable levels by fishing out their predator (e.g., saithe) and reducing mortality amid warming seas. However, such solution may well not be applicable and/or sustainable.



Foodweb structure of the model. Nodes represent functional groups within the ecosystem; the size of the node is proportional to the biomass it represents. Biomass flows enter a node from the bottom and exit a node from the top and are scaled to flow proportion. The y-axis indicates the trophic level of the functional groups.



(a) Species thermal response functions (for Norway lobster, a eurythermal species (red, optimum temperature = 13.8 °C) and for herring, a boreal species (blue, optimum temperature = 4.6 °C)). (b) Cumulative temperature tolerance graphs ranked by optimum temperature (bold black line) also showing maximum (upper limit of dark orange bar) and minimum (upper limit of white bar) temperatures and the 90th (upper limit of light orange bar) and 10th (upper limit of blue bar) percentiles for each functional group.

References

González-Pola, C. *et al.* 2018. ICES report on Ocean climate 2017. – ICES Coop. Res. Rep. 345: 119.

Serpetti, N., Baudron, A.R., Burrows, M.T., Payne, B.L., Helaouët, P., Fernandes, P.G., Heymans, J.J., 2017. Impact of ocean warming on sustainable fisheries management informs the ecosystem approach to fisheries. Sci. Rep. 7, 1–15. https://doi.org/10.1038/s41598-017-13220-7.

Ecoregion H. Greater North Sea

A discussion of agent-based methods in fisheries management with reference to the North Sea (contributed by Robert B. Thorpe)

Stock assessment models are typically area-based, but an alternative treatment based on agents, or "super-individuals" of similar biological state is also possible. This alternative approach has several advantages: a) recruitment, growth, and predation can emerge from internal dynamics + environmental forcing, b) climate and other environmental mechanisms can be explicitly represented, c) age-weight/length relationships can be explicit, d) fisheries-induced evolution can be modelled directly, e) models are potentially good as communications tools, f) movement can be explicitly modelled, g) can be good at heterogenous responses/mechanisms, h) can be used for bio-accumulation.

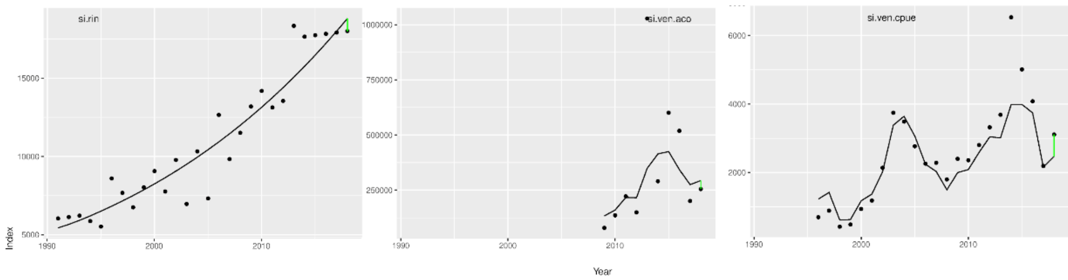
However, there are some big disadvantages. The models can be very slow, leading to problems with fitting, estimating uncertainty, and using in MSEs. They may be hard to fit to data, and it may be difficult to determine appropriate rues for agents. Highly stochastic outputs may be hard to interpret, and data storage needs may be high. Thus it is not clear how useful they might be, particularly as the super-individual may be needed for computational efficiency, but blurs the direct link to life-history, whilst a gridded array of bulk models may capture many of the advantages of agent-based approaches without taking as long to run.

The agent-based concept was illustrated for the North Sea using a 21-stock model built from Ken Andersen's equations. The biomass fits to survey or assessment were generally good for magnitude and often good for trend, with some notable exceptions. The model wanted to collapse cod to lower levels than observed, but suggested it would recover if fishing was reduced to FMSY. The model also generated stock-recruit curves that looked reasonable. M2 was very low for the rays, otherwise quite high, though it decreases with age. More development work is needed, but the model may have some utility alongside other approaches

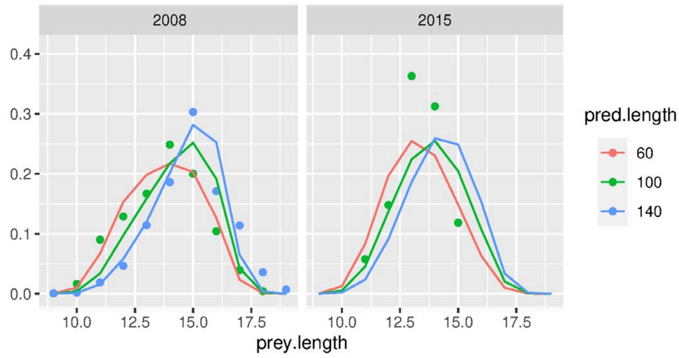
Ecoregion I. Baltic Sea

A vendace-ringed seal model for the Bothnian ecosystem (contributed by Valerio Bartolino)

The Bothnian Sea and Bay (respectively, SD 30-31) are important fishing grounds for pelagic fish species and the major reproduction area for ringed seals in the Baltic Sea. Salinity, temperature and ice cover are among the main drivers of the system and many species live at their physiological limits within this region. Seals are the top predators in this system, and preliminary data show that 60–70% of the ringed seal diet is made of vendace and herring which are both intensively fished and represent large portion of the landed value in the area. After a record low in the 1960s-1970s, the ringed seal population, like for other seals from the Baltic, experienced a steady increase which continues at present with the result of increasing competition and conflicts between seals and fisheries. This motivated the implementation of a multispecies model representing the trophic interaction between ringed seal and its fish preys. The model presented in 2020 at WGSAM is an age-length structure model based on the Gadget framework with dynamic seal and vendace populations. The model fits compositional data on fish from fisheries and survey as well as survey indices for both vendace and seal. Seal stomach data are also used by the model. Estimation of seal-prey size preference appears reliable while available information on species composition in their diet is insufficient for robust estimates and more stomach data are required. Further work is planned on the model, including (1) use of new seal stomach data (currently under analysis), (2) implementation of a dynamic herring model, (3) estimation of multispecies Fmsy.



Model fitting of the seal population size index (left), and vendace acoustic survey index (center) and commercial CPUE (right).



Observed (dots) and predicted (lines) vendace size composition in stomachs of small, medium and large ringed seal stomachs in 2008 and 2015 quarter 2.

Ecoregion L. Oceanic Northeast Atlantic

No update

Ecoregion M. Azores

No update

Ecoregion N. Bay of Biscay and the Iberian Coast

Applications of Ecopath with Ecosim in Portuguese continental waters (contributed by Alexandra Silva and Dorota Szalaj)

An Ecopath and Ecosym model was configured to represent the continental waters off the Portuguese coast in the period 1986–2017 (Veiga-Malta *et al.* 2019; Szalaj *et al.* 2021a). The model focus on small pelagic fish, mainly sardine, and has been applied to investigate the relative importance of trophic interactions, fishing and environmental forcing on the ecosystem and on sardine (Szalaj *et al.* 2021a; see figure below). An application of the model to evaluate the influence of various scenarios of fishing intensity, changes in predator abundance and IPCC SST scenarios in the development of the ecosystem and of the sardine stock in the next years is in preparation. Inputs and outputs of the EwE model, such as biomass, catch, trophic and Ecological Network Analysis indicators were used to test a hypothesis about the occurrence of regime shifts using methods of Integrated Trend Analysis (Szalaj *et al.* 2021b). The model structure includes 33 functional groups, juvenile and adult sardine stanza, an environmental response function using

SST as a driving force of adult sardine spawning and a forcing on sardine Egg production using SSB as a forcing parameter. The model fitted well to most functional groups with observation data and provided a broad understanding of the ecosystem functioning and of trophic interactions. Knowledge gaps are related to observations of top predators and plankton, diets of some functional groups, the use of bottom trawl surveys data and the lack of fishing mortality estimates for several groups. The extension of the model area to span the management areas of most fishing resources in the Iberian Peninsula waters is acknowledged and may help to support an advance to EAFM in the region.

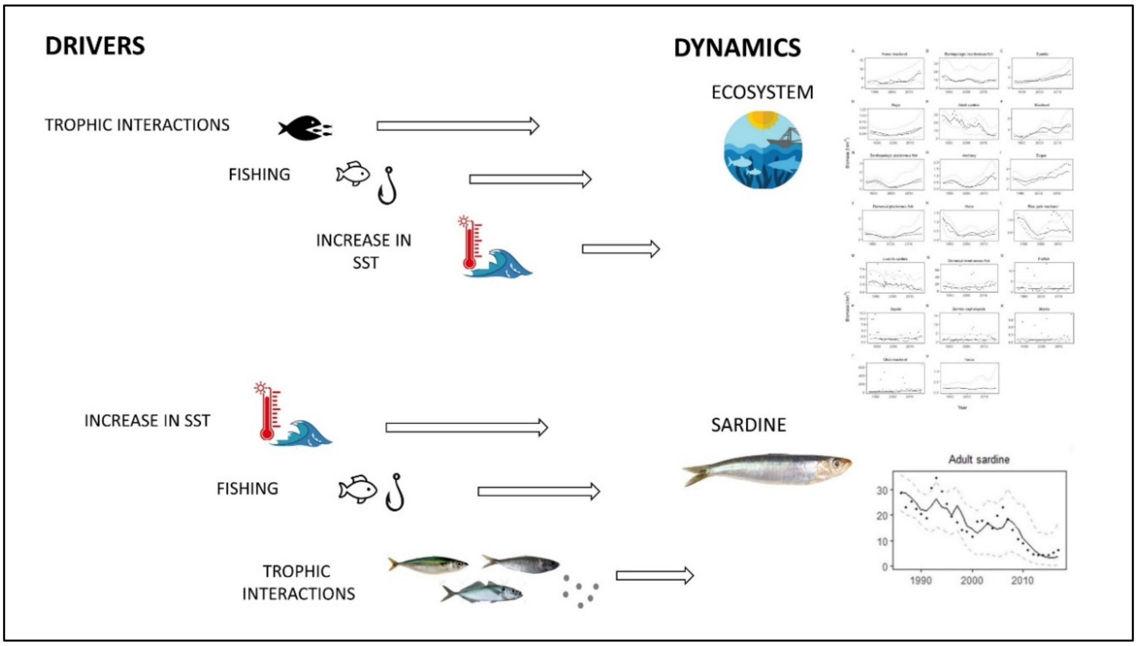


Diagram of the relative importance of trophic interactions, fishing and environmental drivers on the dynamics of the Portuguese continental shelf ecosystem and on sardine.

Ecoregion O. US Northwest Atlantic (and other regions)

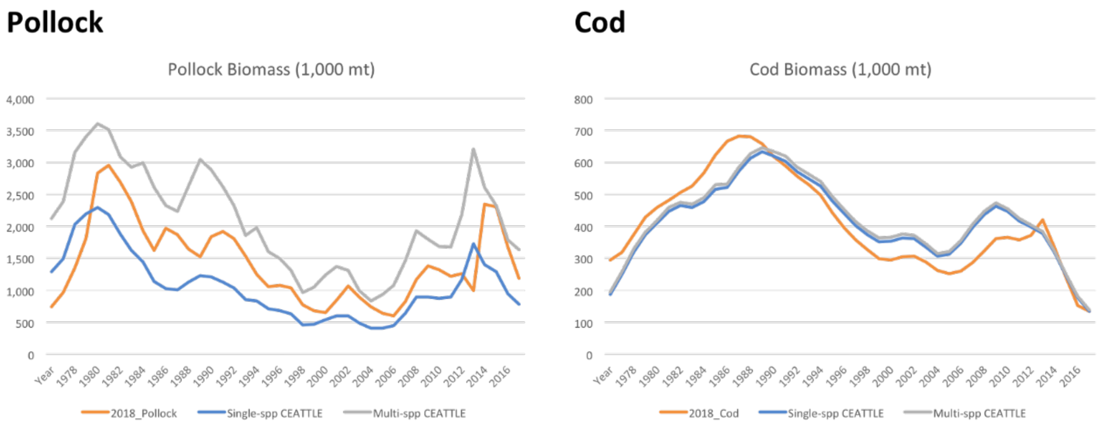
Gulf of Alaska

Rceattle model (contributed by Grant Adams)

Grant Adams submitted an overview of the new multispecies model CEATTLE implemented in R for three species in the Gulf of Alaska by Grant Adams, Kirstin Holsman, Kerim Aydin, Steve Barbeaux, Martin Dorn, Anne B. Hollowed, Jim N. Ianelli, Ingrid Spies, Ian J. Stewart, and André E. Punt. This model had been previously developed in ADMB for three interacting Bering Sea species.

Rceattle is a flexible multi-species modelling package built with R/TMB. The major updates from the ADMB version of CEATTLE include the ability to fit multiple surveys/fisheries flexibly, to implement time varying catchability/selectivity, to have a two sex model, and to estimate predator/prey suitability. Rceattle includes aging error/bias corrections, random effects for selectivity, catchability, and recruitment, and can include fixed predator-at-age (e.g. extended single species model).

Rceattle has fit 3 different MSCAA-models (Adriatic, GOA, Bering). The new Gulf of Alaska (GOA) model specifications include three species, Walleye Pollock (sexes combined), Pacific Cod (sexes combined), and arrowtooth flounder (2 sex) and covers the years 1977 to 2018. The model fits to the same data-sets as AFSC single species assessment models as well as diet data and energetics.



Comparison of estimated pollock and cod biomass from three single species and CEATTLE models in the Gulf of Alaska.

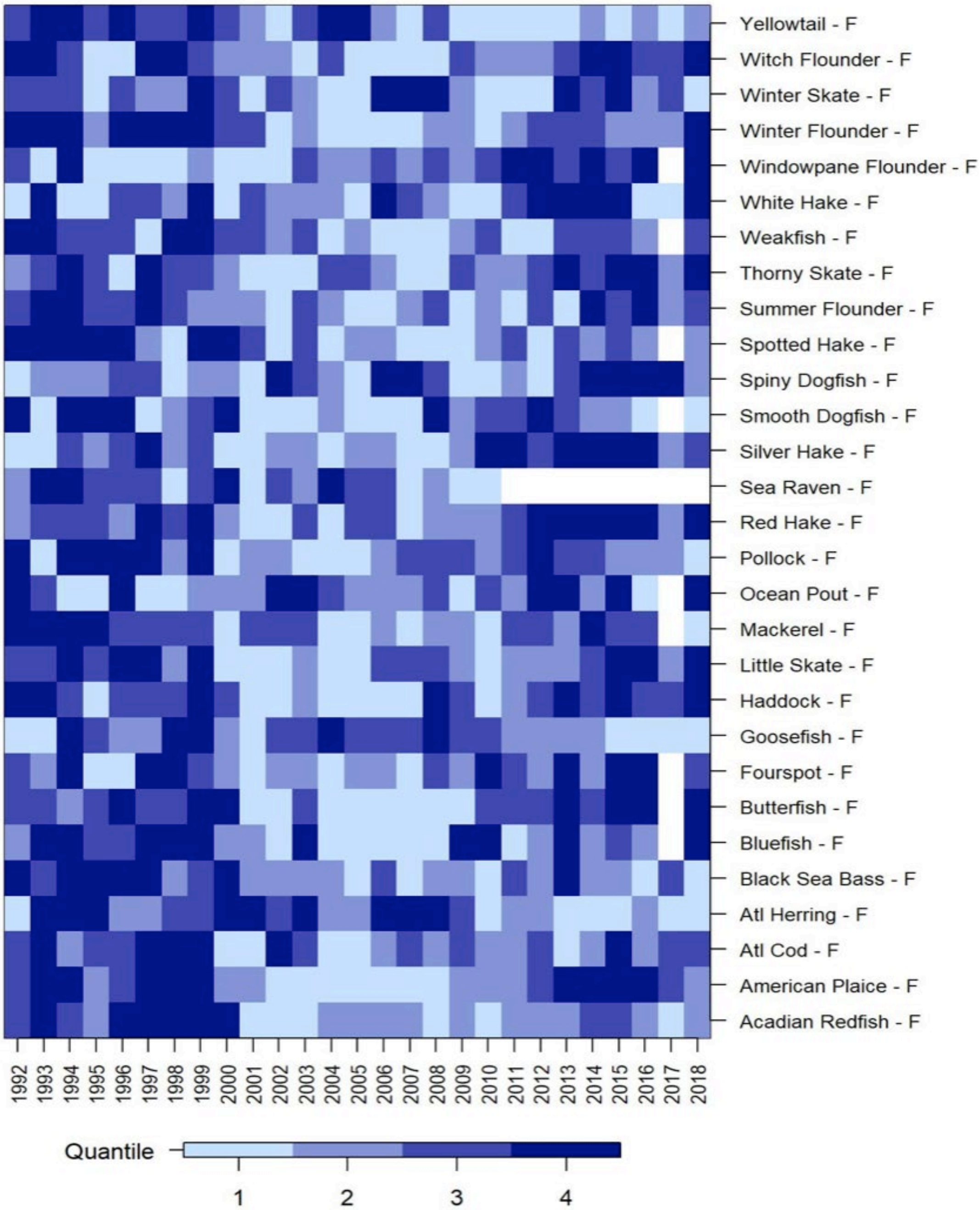
Age-1 predation mortality estimated by Rceattle for three Gulf of Alaska species.

We report time-series of biomass and proportion of age-1 predation mortality estimates for walleye pollock (Gadus chalcogrammus), Pacific cod (Gadus macro- cephalus) and arrowtooth flounder (Atheresthes stomias), from the Gulf of Alaska (GOA). Estimates are based on residual mortality inputs (M1), model estimates of annual predation mortality (M2), and fishing mortality (F) produced from the multi-species statistical catch-at-age assessment model (known as CEATTLE; Climate- Enhanced, Age-based model with Temperature-specific Trophic Linkages and Energetics; Holsman, Ianelli, Aydin, Punt, & Moffitt, 2015). Specifically, we developed a flexible multi-species stock assessment package (Rceattle) based on CEATTLE in R and Template Model Builder (Kristensen, Nielsen, Berg, Skaug, & Bell, 2015) to allow for the fitting of multiple sources of data, multiple selectivity functions, time-varying selectivity, time-varying catchability, random effects (recruitment, selectivity, catchability), and fixed predator abundance (similar to extended single-species models). The package is flexible such that the parameterization and data used for the most recent stock assessment models of the above species is possible (Barbeaux *et* *al.*, 2018; Dorn, Aydin, Jones, Palsson, & Spalinger, 2018; Spies & Palsson, 2018). The GOA model is fit to data from five fisheries and seven surveys, including both age and length composition assumed to come from a multinomial distribution. Model estimates of M2 is empirically driven by bioenergetics based consumption information and diet data from the GOA to inform predator-prey suitability. The model was fit to data from 1977 to 2018. Pollock were primarily consumed by older conspecifics in the early part of the time-series, while arrowtooth flounder has become the main consumer since the mid 1980's. On average pollock cannibalism accounts for 32%, Pacific cod accounts for 8%, and arrowtooth flounder accounts for 60% of total age 1 predation mortality on pollock (M2).

Northeast US Shelf

Is climate change affecting fish condition factor? (contributed by Laurel Smith and colleagues)

Laurel Smith, Michael Fogarty, Charles Perretti, Mark Wuenschel, and Andy Beet used GAM modelling to determine whether observed changes in fish condition on the Northeast US shelf were related to changing ocean conditions. Condition has implications for growth, egg production, recruitment and fishery yield.



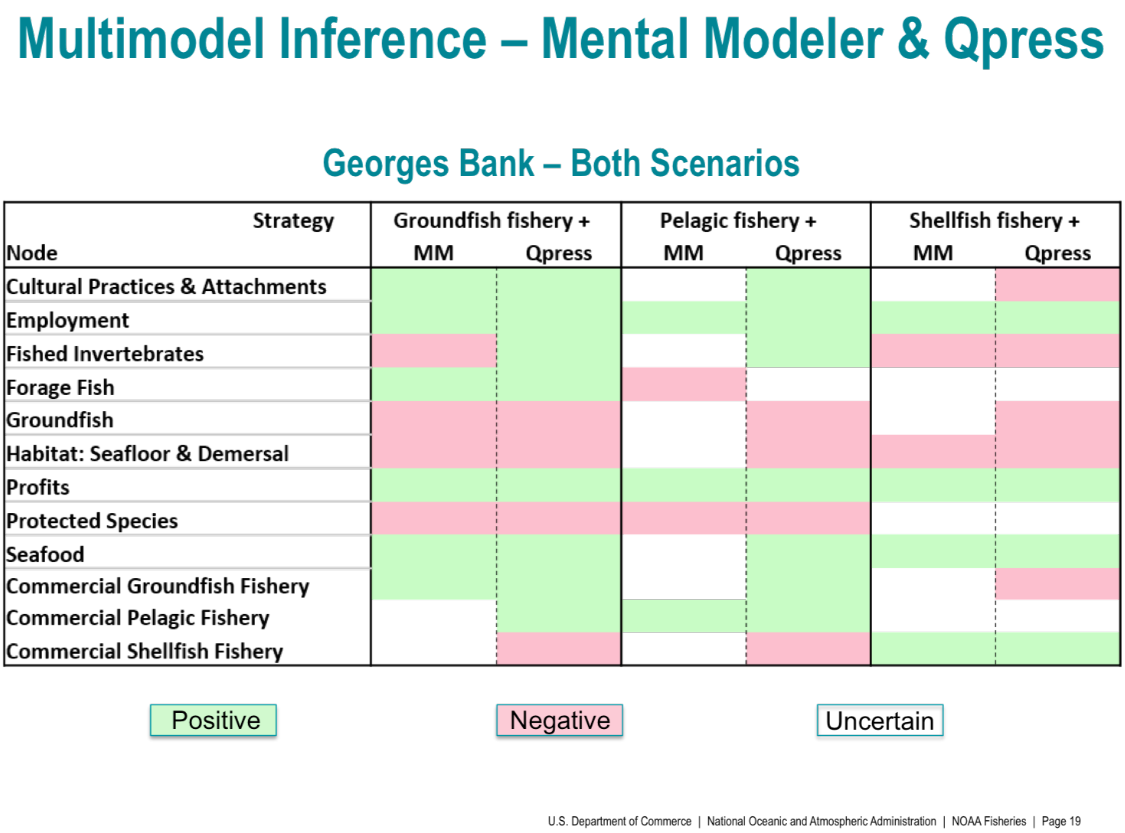
NEUS condition: difference in predicted weight from actual weight at a given length by species and sex.

Initial results indicate that climate change may be impacting fish condition through bottom temperature, copepod size structure and food availability. However, local density dependence was not found to be not a main driver. The analysis is still missing key explanatory variables for condition (e.g. spatial variability) and is continuing.

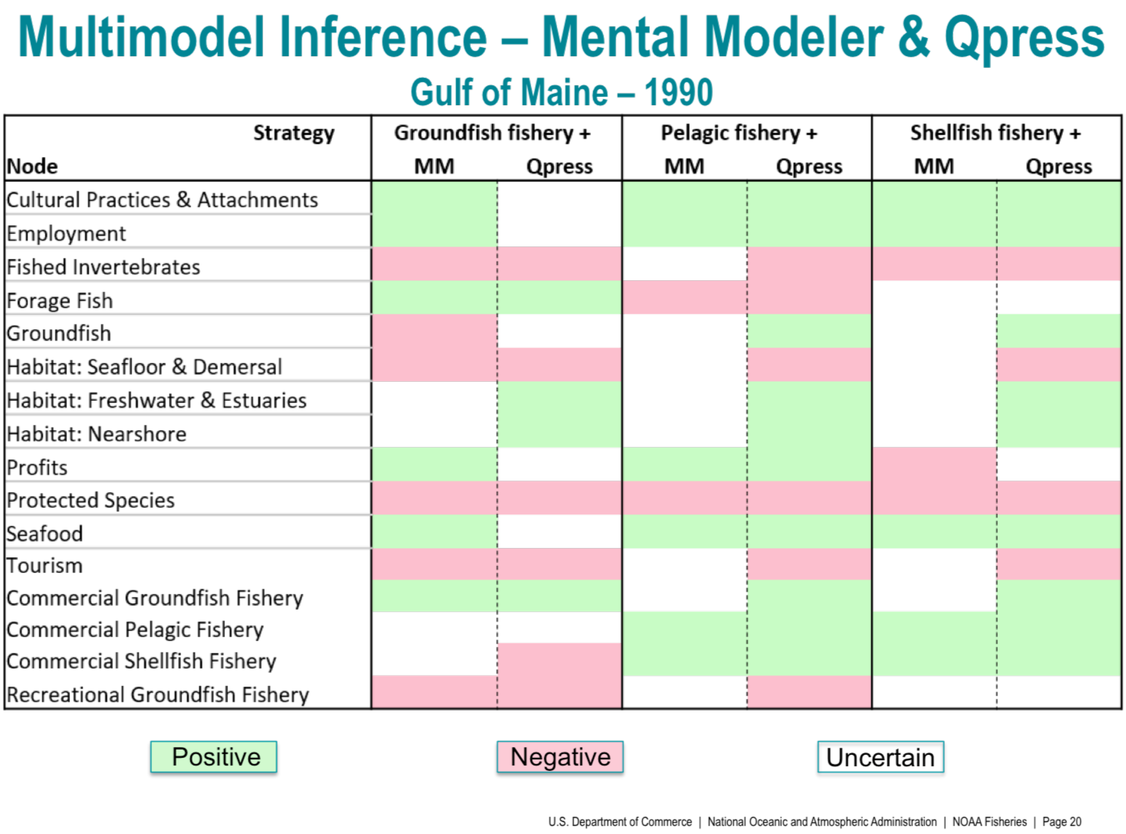
Conceptual modelling for Integrated Ecosystem Assessment (contributed by Robert Gamble and colleagues)

Robert Gamble, Jamie Tam, Sarah Gaichas, Geret DePiper, Sean Lucey, Patricia Clay, Gavin Fay, Paula Fratantoni, Charles Perretti, Patricia Pinto da Silva, Vincent Saba, Laurel Smith, and Robert Wildermuth constructed conceptual models of the Georges Bank and Gulf of Maine ecosystems and used two approaches to evaluate impacts of perturbations on these models. Mental Modeller software was used to develop qualitative static conceptual models, which were then translated to semi-quantitative models using fuzzy-logic cognitive mapping. Qpress (software implemented in R) was applied to perform a stochastic version of loop analysis. Qpress measures the likelihood of data under original model compared to a perturbed model.

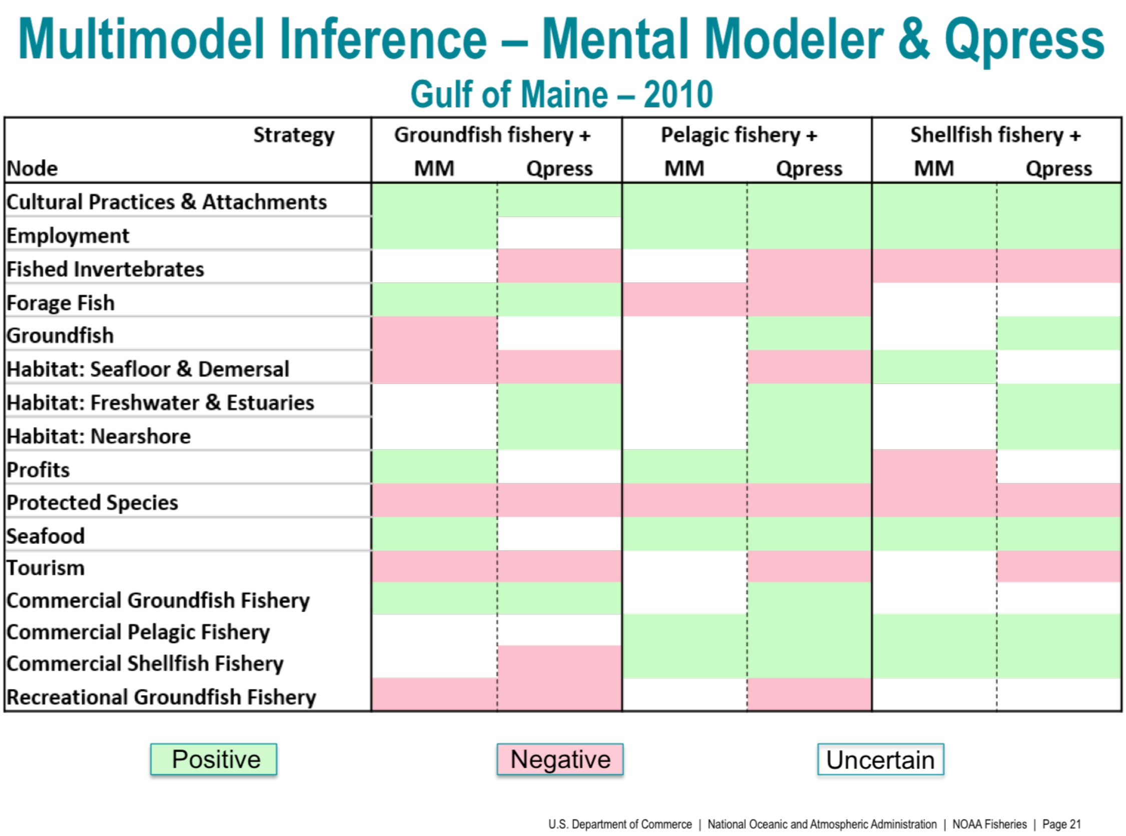
Comparisons between perturbations across ecosystems and modelling frameworks showed some similarities and differences. For example Georges Bank showed no difference in outcomes between 1990 and 2010, while the Gulf of Maine did. While teh direction of change due to perturbations between Mental modeller (MM) and Qpress were mainly consistentn, for some key groups such as forage fish on Georges Bank, they differed.



Georges Bank 1990 and 2010.



Gulf of Maine 1990.



Gulf of Maine 2010.

This ongoing work continues to explore tools that can address complex relationships across disciplines (e.g. physical, biological, and human dimensions). Conceptual models can give everyone a common understanding of the system, and have the advantages of being relatively quick to build and modify. These tools can incorporate uncertainty and can be used for scenario and strategy testing.

Northeast US Atlantis model development

Two new github repositories are available to track development of the NEUS atlantis version 2.0:

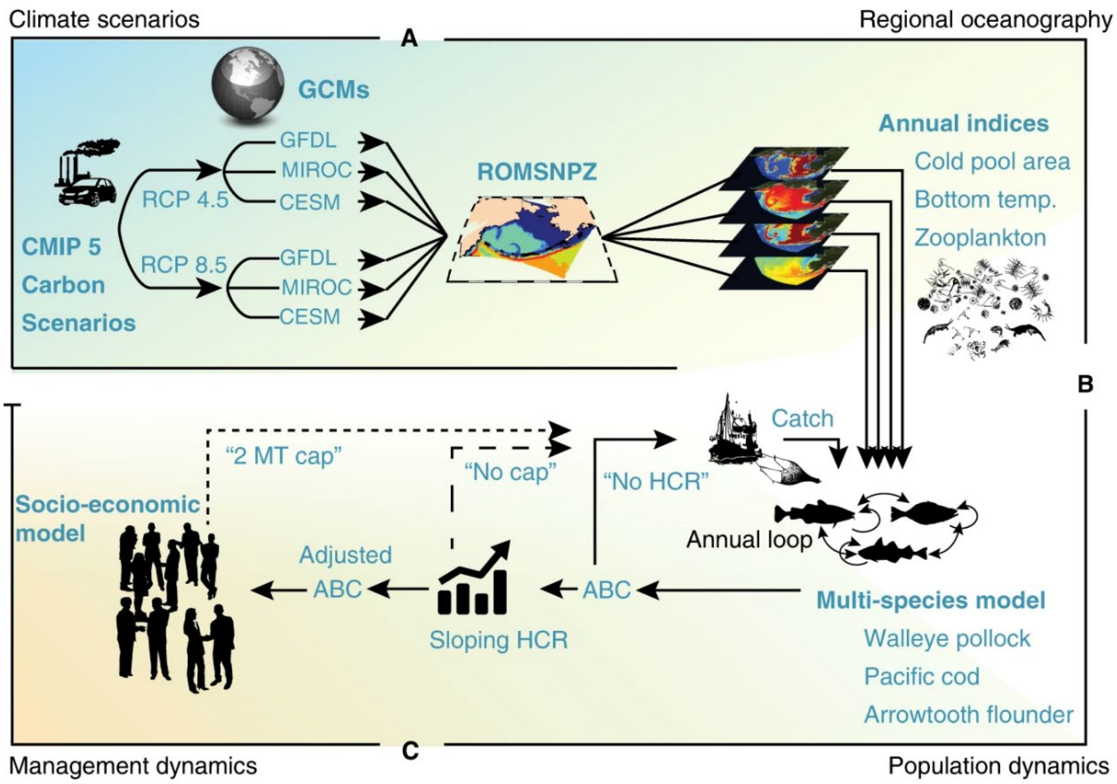
https://github.com/NOAA-EDAB/atneus_RM/wiki

https://github.com/NOAA-EDAB/atneus_RM/blob/output_testing/diagnostics/DiagnosticsDoc.Rmd

Bering Sea

Climate projections with multispecies model (contributed by Kirsten Holsman and colleagues)

A new paper By Kirsten Holsman and colleagues uses the CEATTLE multispecies model with downscaled global climate projections to evaluate impacts to managed species in the Bering Sea under different management scenarios (Holsman *et al.* 2020). The multispecies model used climate-forced ROMS-NPZ output within temperature- and zooplankon-driven growth, predation, and recruitment functions for 3 interacting species: walleye pollock, Pacific cod, and arrowtooth flounder. Figure 1 from the paper demonstrates the model linkages in the study.



Holsman et al 2020, Model Coupling Framework

Legend from the paper: "a. Regional downscaling where three global climate models driven by the IPCC AR5 CMIP5 emission scenarios determine boundary conditions of the coupled

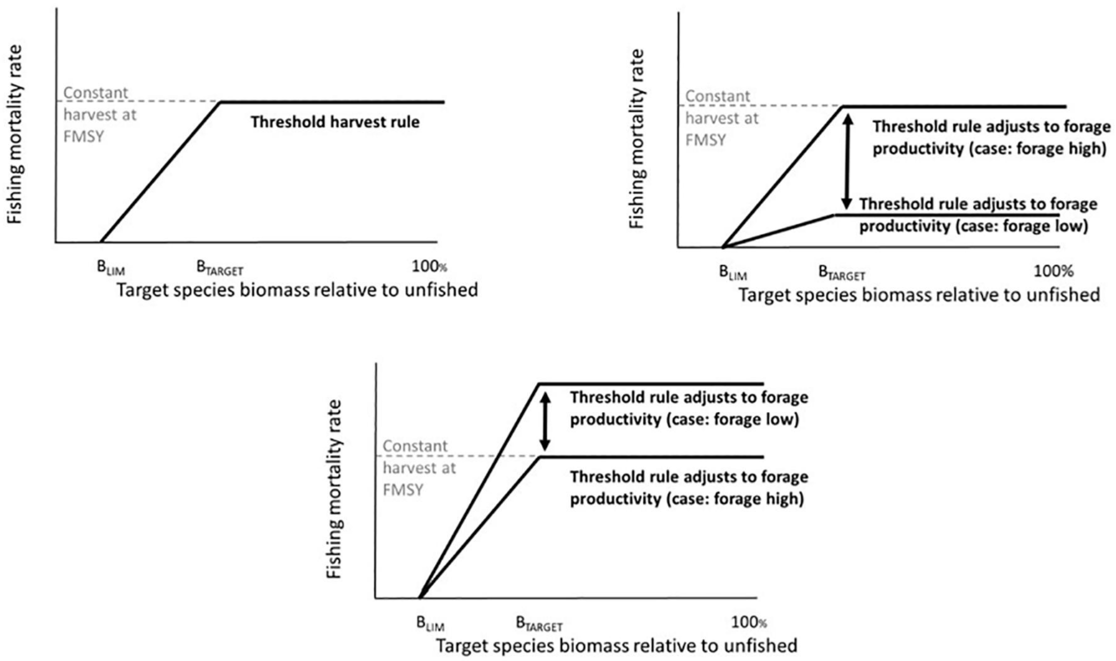
ROMSNPZ high resolution oceanographic model for the Bering Sea, AK. b Biological downscaling of annual indices from the ROMSNPZ were used to drive thermal parameters in the CEATTLE model (i.e., weight-at-age and predation) as well as climate-enhanced spawner-recruitment relationships. c Annual harvest recommendations (ABC) from the assessment model which were translated into annual catch using the ATTACH social-economic model of the effect of EBFM policies on harvest"

Overall, the study found that EBFM measures such as the 2 million metric ton total annual catch limit imposed on Bering Sea groundfish fisheries mitigate climate change and preserve fishery benefits up to a point. However, the expected impacts of climate change under the "business as usual" scenario (RCP 8.5) eventually caused pollock and cod stocks to crash even with EBFM measures in place. Using this linked modelling framework, Holsman *et al.* were able to identify a bottom temperature threshold (2.1–2.3 degrees C in summer) above which pollock and cod stocks in the Bering Sea would be likely to decline rapidly.

California Current and Norwegian/Barents Sea

Ecosystem based harvest control rules (contributed by Isaac Kaplan and colleagues)

A new paper by Isaac Kaplan, Cecilie Hansen, and colleagues used Atlantis models to evaluate the performance of different ecosystem-based harvest control rules across two ecosystems: the California Current and Norwegian/Barents Sea (Kaplan *et al.* 2020). Harvest control rules that reduced fishing mortality (F) below a target species biomass threshold were compared to those that maintained a constant F at MSY level regardless of target species biomass. In addition, harvest control rules that either increased or decreased target species fishing mortality rate in response to forage biomass were compared to a more traditional threshold F based only on the target species productivity.



Kaplan et al 2020.

Legend from the paper: "Top left panel: Threshold harvest control rule and constant fishing mortality rate at FMSY. Top right panel: Threshold harvest control rule that decreases F when the forage base declines. Bottom panel: Threshold harvest control rule that increases F when the forage base declines."

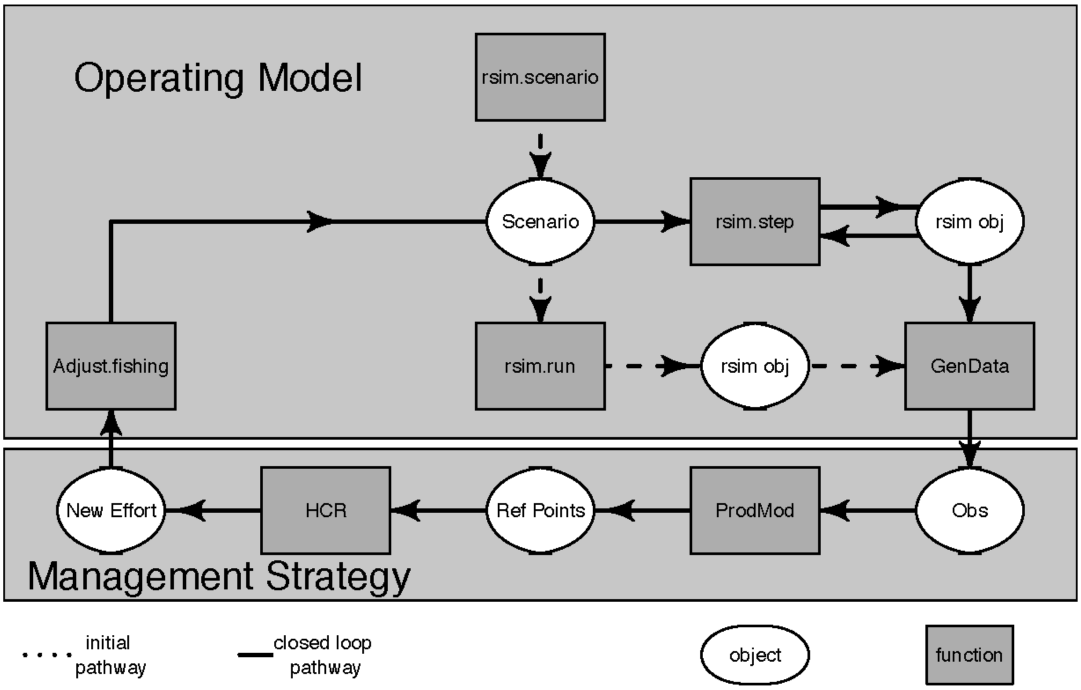
In both systems, ecosystem models supported results from single species modelling that the harvest control rules reducing F when target species biomass fell below a threshold generally resulted in higher target species biomass overall in the ecosystem (target species were Atlantic mackerel in the Norwegian/Barents Sea and Pacific hake in the California Current).

Harvest control rules that changed the upper limit of target species F based on forage (zooplankton) abundance in the system increased catch variability in both ecosystems because zooplankton is highly variable. In addition, control rules that increased target species F when zooplankton declined led to more impacts on other species in each ecosystem model than other tested policies (in particular in the Norwegian/Barents Sea). Overall, the study demonstrated the utility of Atlantis and other ecosystem models for testing proposed harvest strategies and evaluating implications across the full range of species in the ecosystem rather than target species only.

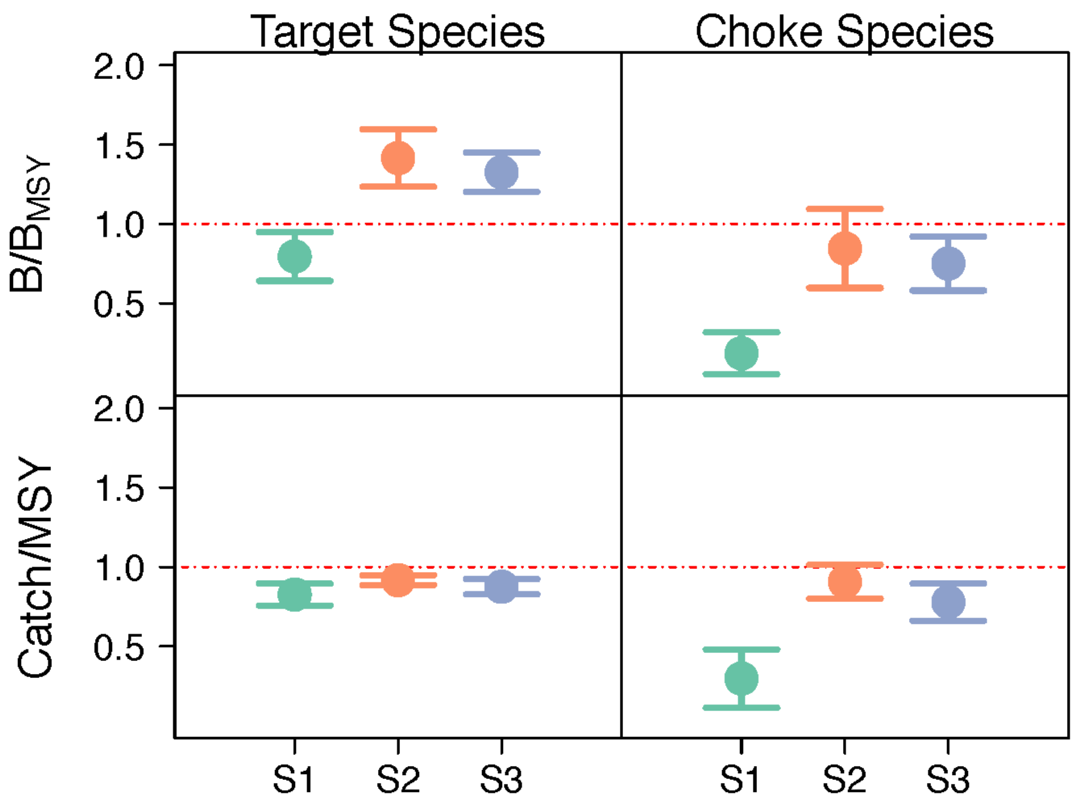
Northeast US Shelf

Rpath with MSE capabilities (contributed by Sean Lucey and colleagues)

Rpath is an open source version of Ecopath with Ecosim that has been implemented in R and is available on github (https://github.com/NOAA-EDAB/Rpath). A new paper by Sean Lucey and colleagues demonstrates Rpath's structure and capabilities (Lucey, Gaichas, and Aydin 2020). A newly accepted paper gives an overview of a new Rpath feature that facilitates management strategy evaluation (Lucey, Sean M., Kerim Y. Aydin, Sarah K. Gaichas, Steven X. Cadrin, Gavin Fay, Michael J. Fogarty, and Andre Punt. Accepted. Evaluating fishery management strategies using an ecosystem model as an operating model. Fisheries Research). The paper demonstrates the operating model logic implementing the management strategy evaluation, and gives a simple example contrasting management strategies for different target species within the ecosystem. Similar to the Atlantis paper above, this work demonstrates the utility of implementing management strategies within an ecosystem model so that the full suite of effects to both target and non-target species can be evaluated. Here, "choke" species are those with lower harvest limits due to depleted conditions which act as constraints in mixed species fisheries where they are caught together with more abundant species.



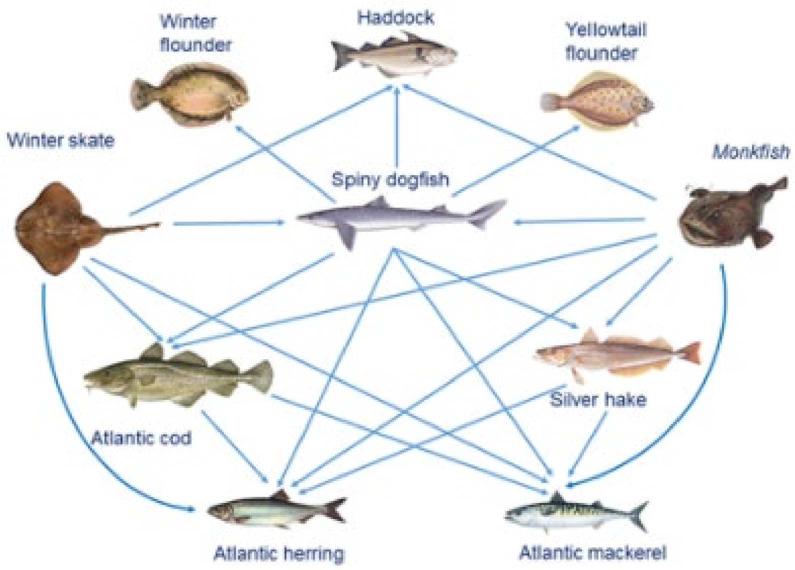
Rpath MSE model logic.



Biomass and catch comparisons for target and limiting (choke) species under three management scenarios in an Rpath foodweb model.

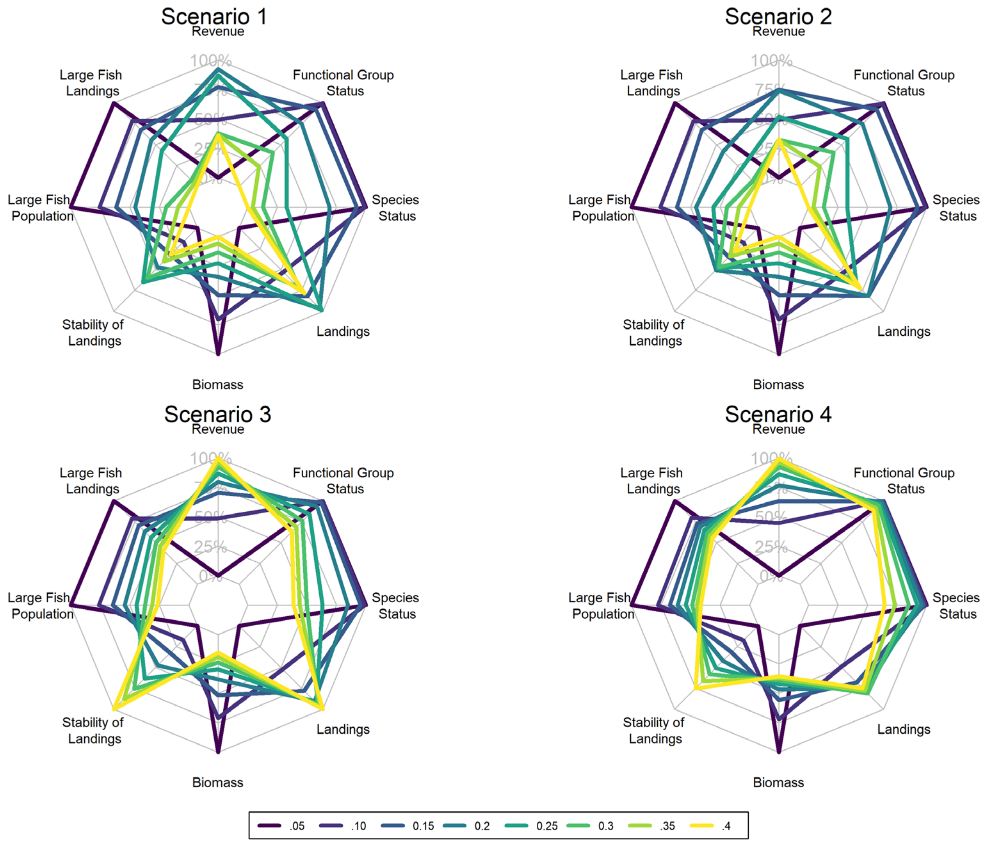
Ongoing EBFM modelling for New England

The US New England Fishery Management Council (NEFMC) is requesting model scenarios in support of its EBFM development. The length-structured multispecies simulation model Hydra has been set up to model 10 interacting species on Georges Bank and programmed by Andy Beet to evaluate a wide range of potential EBFM management procedures.



Georges Bank foodweb.

Four example scenarios are pictured in this figure and described below.



Outcomes of 4 management scenarios for simulated Georges Bank species from a length structured operating model.

Scenario 1: Fixed exploitation rate. Exploitation rates = 0.05–0.4 in increments of 0.05. Floor assessed at the complex level. If the floor* of any complex is breached any further catch of this complex is considered a discard.

Scenario 2: The same as Scenario 1 with one addition. Floors assessed as the species level. If the floor* of any species is breached any further catch of this species is considered a discard.

Scenario 3: Variable exploitation rate. Starting exploitation rates = 0.05–0.4 in increments of 0.05. Each species complex is associated with a single fishing fleet. Species are still caught by multiple fleets, but when a species/complex becomes depleted, management actions only occur on the associated fleet. Each species complex is associated with the fleet that is considered the largest exploiter of the complex. The fishing fleets impact (exploitation) on the complex is adjusted through time5 (as depicted in HCR figure) when the complex biomass falls below 40% unfished biomass.

Scenario 4: The same as Scenario 3 with one addition. The fishing fleets impact on the complex is adjusted through time (as depicted in Figure 4) as the biomass of an individual species within the complex falls below 40% unfished biomass (50% for Elasmobranchs). This can be thought of as additional species protection

Work continues to deliver additional features for Council review.

Associated GitHub repositories

hydra-sim Wiki https://github.com/NOAA-EDAB/hydra_sim/wiki

hydradata https://github.com/NOAA-EDAB/hydradata

LeMANS https://github.com/NOAA-EDAB/LeMANS

mscatch https://github.com/NOAA-EDAB/mscatch Multispecies fishery catch data

Online Resources

Alaska multispecies and ecosystem models https://www.integratedecosystemassessment.noaa.gov/regions/alaska/ebs-integrated-modelling

California Current Future Seas MSEs https://www.integratedecosystemassessment.noaa.gov/regions/california-current/cc-projects-future-seas

Mid-Atlantic ecosystem approach https://www.mafmc.org/eafm

New England example fishery ecosystem plan https://s3.amazonaws.com/nefmc.org/3_Draft-example-Fishery-Ecosystem-Plan-eFEP_190830_113712.pdf

References

Holsman, K. K., A. C. Haynie, A. B. Hollowed, J. C. P. Reum, K. Aydin, A. J. Hermann, W. Cheng, *et al.* 2020. "Ecosystem-Based Fisheries Management Forestalls Climate-Driven Collapse." *Nature Communications* 11 (1): 4579. https://doi.org/10.1038/s41467-020-18300-3.

Kaplan, Isaac C., Cecilie Hansen, Hem Nalini Morzaria-Luna, Raphael Girardin, and Kristin N. Marshall. 2020. "Ecosystem-Based Harvest Control Rules for Norwegian and US Ecosystems." *Frontiers in Marine Science* 7: 652. https://doi.org/10.3389/fmars.2020.00652.

Lucey, Sean M., Sarah K. Gaichas, and Kerim Y. Aydin. 2020. "Conducting Reproducible Ecosystem Modelling Using the Open Source Mass Balance Model Rpath." *Ecological Modelling* 427 (July): 109057. https://doi.org/10.1016/j.ecolmodel.2020.109057.

Annex 4: ToR C

Skill assessment: Establish and apply methods to assess the skill of multispecies models intended for operational advice

Improving confidence in ecosystem models: the sensitivity analysis of an Atlantis model (contributed by Chloe Bracis)

We performed a sensitivity analysis (SA) of the Atlantis-EEC (Eastern English Channel) model for the growth, mortality and recruitment parameters (i.e., those that are most frequently calibrated). There are few SAs of Atlantis models or other complex ecosystem models, and those that do exist tend to be fairly limited. This is due to the combined challenges of long running times and large numbers of parameters for these models.

We utilizes several techniques to help address these challenges

- Use a function to represent age-structured parameters
- Moved correlated parameters together
- Made use of Ifremer's Datarmor supercomputer to execute the simulations
- Used the Morris SA method, which is a global analysis with relatively few simulation runs and allows detecting non-linear/interaction effects

Findings

- Effects generally non-linear and/or with interactions, rather than linear.
- No parameters were unimportant, particularly for stability
- Most broadly influential were those for top predators (recruitment and juvenile mortality rate) and plankton (growth rates), with a group's own parameters also important.
- Of secondary but still broad influence were the benthos invertebrate groups, particularly growth rates but also mortality rates.

Implications

- Could use SA to target/justify data collection needs
- Could use SA to inform uncertainty analysis (i.e. analyse those parameters sensitive for target species/group and uncertain from data pedigree)
- Would be interesting to compare with other Atlantis models and other ecosystem models as more SAs are done to see what parts are general to Atlantis (probably dominance of nonlinear/interaction effects and importance of plankton groups) and which may be more specific to this particular implementation (possibly importance of benthos given it's a relatively shallow system)

Bracis, C., Lehuta, S., Savina-Rolland, M., Travers-Trolet, M., & Girardin, R. (2020). Improving confidence in complex ecosystem models: The sensitivity analysis of an Atlantis ecosystem model. Ecological Modelling, 431, 109133. https://doi.org/10.1016/j.ecolmodel.2020.109133

Validating and assessing uncertainty of ecosystem models, and relating these to corresponding stock assessment models in New Zealand (contributed by Vidette McGregor)

The initial conditions of ecosystem models have some level of uncertainty. The sensitivity of the Chatham Rise Atlantis model dynamics to changes in the initial conditions were tested. Some species groups were found to be more sensitive to changes in the initial conditions than others were.

McGregor, V. L., Fulton, E. A., & Dunn, M. R. (2020). Addressing initialisation uncertainty for end-to-end ecosystem models: application to the Chatham Rise Atlantis model. PeerJ, 8, e9254. https://doi.org/10.7717/peerj.9254

Fragile ecosystems, robust assessments? (contributed by Sarah Gaichas)

Mathematical models have two primary and related uses in marine natural resource management: estimation of the current state of a system, and projection of the consequences of alternative future management strategies on that system. Models used in fisheries management have a wide range of complexity, and can be applied at multiple levels from single stocks to multispecies communities. However, formal skill assessment is not routinely applied to these models, primarily because observations of modelled quantities can be highly uncertain, and skill assessment evaluates how well a given model reproduces the truth. Here, we demonstrate methods for using ecosystem models as simulators to provide both a true system state for skill assessment, and datasets for input into fisheries stock assessment models with realistic observation and process uncertainty.

The California Current and Nordic/Barents Seas are experiencing rapid global change, fundamentally altering the productivity of ecosystems and fish stocks. To facilitate the development of fishery management advice that is robust to climate change, we tested the performance of stock assessment modelling approaches under simulated climate scenarios across these two ecosystems. As 'operating models' or virtual testbeds, we applied Atlantis ecosystem models, configured for the California Current and Nordic/Barents Seas, and forced with scenarios for warming ocean temperature. These scenarios project conditions in the 2060's, with associated impacts on biomass dynamics via changes in fish growth, trophic interactions, and predation mortality. These ecosystem models are spatially explicit and include biological groups ranging from primary producers to top predators; here we focus primarily on key harvested species including Pacific sardine (*Sardinops sagax*) and Pacific hake (Merluccius productus), and Northeast Arctic cod (*Gadus morhua*) and Norwegian spring spawning herring (*Clupea harengus*). Using a new R package, AtlantisOM, we simulate survey and fishery sampling from Atlantis output, including the uncertainty and bias associated with survey and catch observations, before passing data to a Stock Synthesis assessment. Within Stock Synthesis, we will evaluate the efficacy of different modelling assumptions (e.g., time-varying, empirical, or constant) on growth and natural mortality parameters to account for changing productivity driven by climate change. We will evaluate stock assessment performance by quantifying the bias and precision of derived quantities related to population size, fishing intensity, and depletion, and by evaluating management performance on forward projections in which fishing rates were set based on reference points estimated in the assessment.

Kaplan, I. C., Gaichas, S. K., Stawitz, C. C., Lynch, P. D., Marshall, K. N., Deroba, J. J., ... & Link, J. (2021). Management strategy evaluation: allowing the light on the hill to illuminate more than one species. Frontiers in Marine Science, 8, 688. https://doi.org/10.3389/fmars.2021.624355

Atlantisom R Package https://github.com/r4atlantis/atlantisom

Performance of a state-space multispecies model: what are the consequences of ignoring predation and process errors in stock assessments? (contributed by Vanessa Trijoulet)

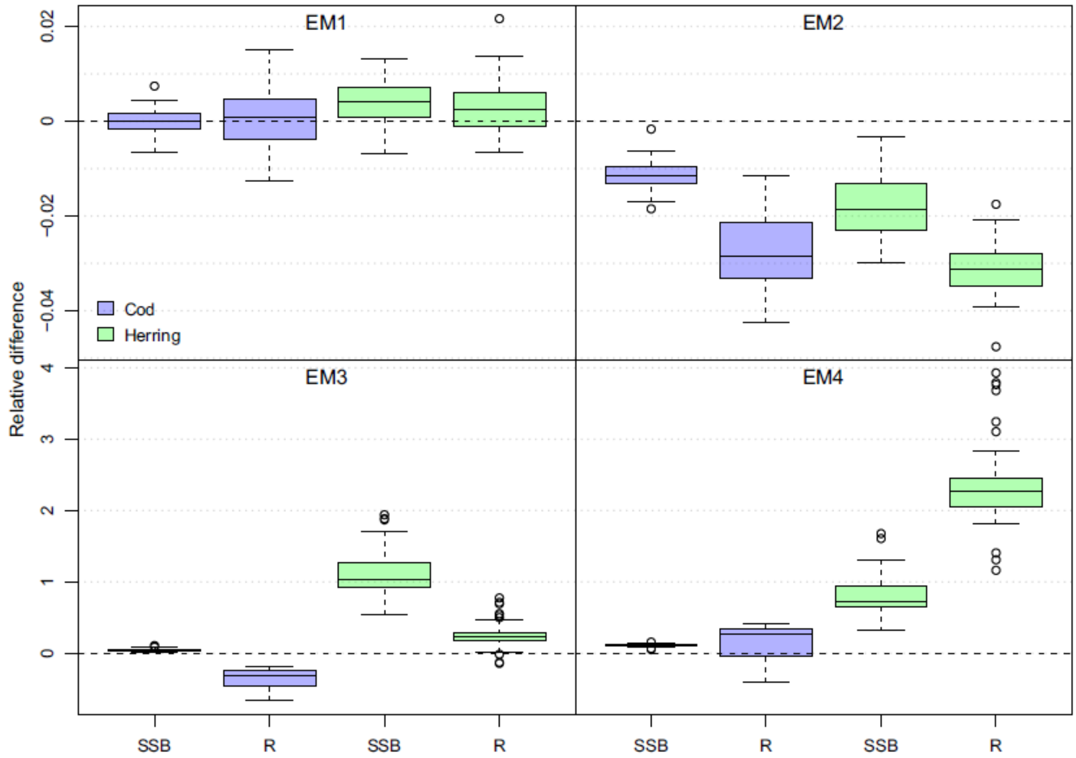
The recently published study from Trijoulet *et al.* (2019a) was presented during the meeting. It consists in a simulation analysis to investigate the consequences of ignoring trophic interactions and process errors in stock assessment models. The multispecies model of Trijoulet *et al.* 2019b was developed to account for process errors on recruitment and numbers at age. The model was used as an operating model to simulate 1000 data sets with errors in observations (catch, survey indices, and stomach contents) and in processes. Four estimation models (EMs), which differ in how they account for trophic interactions and process errors, were fitted to the data sets:

- EM1 was a state-space multispecies stock assessment and had the same configuration as the OM.
- EM2 was a multispecies statistical catch-at-age stock assessment which did not estimate process errors
- EM3 was a single species stock assessment model where trophic interactions were ignored and natural mortality was estimated as a constant over age and time
- EM4 was a single species stock assessment model where trophic interactions were ignored and natural mortality was estimated as a constant over time but varying over age as a function of fish weight

The performance of the EMs was evaluated calculating relative differences between estimated parameters and outputs and parameters and outputs from the OM as a measure of bias. Predictive ability of the EMs was tested by removing the last 5 years of survey indices in the data sets. A proxy reference point, unfished biomass, was estimated on the absolute and relative scale for each EM.

Main conclusions:

- Ignoring predation had the largest impact on stock perception and resulted in large bias in parameters, derived outputs and absolute or relative reference points. Estimating unobserved processes was not sufficient in limiting the bias when natural mortality was misspecified.
- Ignoring process errors had limited bias.
- Looking solely at likelihood values to choose among models is misleading and predictive ability could be used to prevent selecting models that overfit the data.
- Ignoring trophic interactions that occur in marine ecosystems induces bias in stock assessment outputs and results in low model predictive ability with subsequently biased reference points. Assuming a constant mortality over time and/or age could have large consequences on stock perception and reference point estimates and affect resulting management advice.



Median relative differences in spawning stock biomass (SSB) and recruitment (R). Annual values of SSB and recruitment are aggregated within each boxplot. Note the change in the y-axis.

Trijoulet, V., Fay, G. and Miller, T.J. (2019a). "Performance of a state-space multispecies model: what are the consequences of ignoring predation and stochastic processes in stock assessments?" Journal of Applied Ecology DOI: 10.1111/1365-2664.13515

Trijoulet, V., Fay, G., Curti, K., Smith, B. and Miller, T.J. (2019b). "Performance of multispecies assessment models: insights on the influence of diet data" ICES Journal of Marine Science DOI: 10.1093/icesjms/fsz053

Eliciting population spatial structure through Calibration and validation? (contributed by Sigrid Lehuta, Sophie Leforestier, Baptiste Alglave, Stéphanie Mahévas, Youen Vermard)

Sole is one of the most valuable commercial species in the Eastern Channel. Evidences are accumulating to suggest that there is little connectivity between three areas of the channel either at early or adult stages. However, the population is still managed as a single stock with possible risks of overexploitation of one component. Improving the knowledge on population spatial structure and assessing the consequences of ignoring it in management is therefore crucial for its sustainability.

In this context, the ISIS-Fish model has been parameterized in order to represent three contrasted hypotheses of stock structure from a unique stock to three independent populations and an in-between situation with an intermediate level of exchanges of adult fish between zones. The goal was to calibrate all three models and assess if one is more plausible with regard to the data.

Models were calibrated by tuning catchability parameters at age to match annual catch at age of sole for the period 2008–2011. ISIS-Fish was coupled with R-calibrar package, which was developed for the Osmose model and is appropriate for complex models (Oliveros-Ramos, 2016). The method is an evolutionary algorithm (AHR-ES). The robustness of the estimates to the choice of the objective function and algorithm initialization has been assessed and conducted to reject one of the objective functions that provided unstable results. The quality of the fit evaluated first visually then using quantitative metrics (value of the objective function, % error, correlation and model efficiency at various scales (temporal and age structure). The validation process consisted in confronting simulated results to observations not used to constrain the model: catch series extended to 2014, annual numbers at age and spatial distribution of catch per gear were evaluated.

The process was conducted to reject the second model (mixing populations) given its low performances compared to the two others. Both remaining models display excellent correlation with the observations but a systematic underestimation of catch (circa 20%) and overestimation of abundance (circa 80%) was noted and unexplained. The spatial patterns were overall reproduced except for two couples gear-rectangle where error was high and none of the models was significantly better. This suggests rethinking the assumptions about underlying population distribution. Both models were kept for further investigations regarding the performance of current management under uncertain stock structure.

MOSES: Model for the Simulation of Ecological Systems (contributed by Francisco Castro)

MOSES, a model for the simulation of ecological systems, is a species-based, biomass foodweb dynamic model. The processes in the model are based on temperature and body size allometry. The model was applied to the Irish Sea ecosystem, with 400 species. Predator to prey body mass relationships are used as a basis for the diet preferences. Feeding is based on type 3 functional responses for stability. The model was calibrated with the attack rate in the functional response equation, aiming for stability with no extinction and a minimum phytoplankton biomass. Future implementations may be used to assess effects of fisheries on the ecosystem.

Get fit quick – calibrating expensive computer models in a day (contributed by Mike Spence)

Mechanistic multi-species models are a powerful tool for modelling marine ecosystems. Based on ecological principles and inter-species reactions, they can provide more robust long-term predictions than statistical single-species models. However, to be useful for evaluating different management strategies, they must be calibrated to a specific system. Traditionally, this would require computationally expensive runs of the model for many combinations of input parameters, which could take months to complete. Meanwhile, management decisions take place on much smaller timescales. One solution to speed up this process is to use quicker statistical emulators to stand in for model runs and discount regions of the parameter space that are implausible, given the observed data. This means far fewer runs of the model are required for calibration and models can be operationalised much more easily. In this talk, Spence demonstrates these methods, using Gaussian process emulators to calibrate 37 free parameters of a size-based multi-species model of the North Sea. He highlighted that using these methods we can efficiently calibrate the model and answer policy questions on short time scales.

What is model skill? My thoughts (contributed by Mike Spence)

Spence proposed that the "expected value of perfect information" (EVPI), a measure of the expected cost of the uncertainty in a model, could be used to define model skill. This involves using the model to make a specific decision. The idea is inspired by a paper on this topic in health economics (Strong and Oakley 2014).

Mark Strong and Jeremy E. Oakley, (2014) When Is a Model Good Enough? Deriving the Expected Value of Model Improvement via Specifying Internal Model Discrepancies, SIAM/ASA Journal on Uncertainty Quantification 2014 2:1, 106-125 https://doi.org/10.1137/120889563

Testing uncertainty and goodness of fit of dynamic foodweb models before building scenarios (contributed by Igor Celić)

Adherence of dynamic foodweb ecosystem models to observed data represents a challenge, increasing proportionally to models' complexity and data availability from multiple sources. Lack of detailed knowledge for all ecosystem processes, subjective choices when creating the model (structure), large number of parameters and their uncertainty, quality of available data issues, all play a role in making the challenge a general issue. The increasing efforts in building ecosystem models worldwide is making this challenge more common, while regulations and policy makers are asking for operational models able to produce validated and accurate results. For this purpose we used Ecopath with Ecosim (EwE) time-dynamic models for the Adriatic Sea also running model ensembles and estimate the precision and accuracy of foodweb simulations. Commonly, the ensembles in EwE are obtained by varying either or both the steady-state and time-dynamic model parameters, which constitute a general framework for evaluating uncertainty. Similarly, perturbations of environmental constrains and forcing functions might create ensembles that include these sources of uncertainty. However, an expert driven process in which multiple fittings are obtained each time by targeting different groups, according to data quality and model objectives. The process result in an ensemble of fitted models with the same structure, higher than average accuracies of the target groups but with different dynamic responses. Results highlight strengths and weaknesses of different ensembles, as well as the difficulties in calibrating such complex foodweb models. The findings suggest that expert driven recursive fitting procedure result in an ensemble that provides more realistically the complexity of the system and might help placing ecosystem results from management scenarios to a risk analysis framework.

Celić *et al.* 2018. Ecological and economic effects of the landing obligation evaluated using a quantitative ecosystem approach: a Mediterranean case study. ICES JMS, 75(6), 1992-2003. https://doi.org/10.1093/icesjms/fsy069

Celić Igor 2017. Development of an ecosystem model of the northern Adriatic Sea. PhD thesis, University of Trieste, Italy.

Can we determine long-term reference points? A mizer skill assessment for dummies (contributed by Robert B. Thorpe)

Thorpe presented a hindcast evaluation of a 21-stock mizer model that was fitted to a single year (2015), the justification being that mechanisms under-pinning foodweb dynamics should be time invariant. As pointed out in the discussion, the assumption of time invariance may not apply if recruitment variability makes up a large proportion of the stock biomass, given that we do not understand the dynamics of this, and the mizer assumes it is deterministic and related to SSB. This notwithstanding, fits for the longer lived stocks were good for the recent past.

Several mizer models were fitted, each with slightly different choices for parameters representing background resource and recruitment efficiency. All the models were able to fit the recent past, and showed good skill in hindcasting subsequent assessed biomass, when they were evaluated against their ability to predict violations of the limit reference point Blim. Performance was assessed using the odds ratio skill score relative to persisting the last assessment, with all models outperforming persistence on the 0–3 year time horizon.

The models were then used to estimate a multispecies MSY based on a Nash Equilibrium, and the unfished biomass B0. Despite fitting past data and performing well in hindcast, the models produced radically different assessments of MMSY and B0. The conclusion is that our current level of understanding is not enough to enable us to pin down these long-term reference points, because of a) lack of understanding of key mechanisms, and b) the reference point future being too different from the past to be constrained by fits to data. We need to know more about i) system productivity and bottom up impacts, ii) non-predation mortality including environmental shock and senescence, and iii) recruitment, including the rate of conversion of eggs to the smallest "fish".

Annex 5: ToR D

Multi-model advice: Evaluate methods for generating advice by comparing and/or combining multiple models

An R package for ensemble modelling (contributed by James Martindale, Michael Spence and colleagues)

- In his 2018 paper "A general framework for combining ecosystem models", Michael Spence introduced a fully Bayesian model ensemble framework. This talk gives an overview of an upcoming R package for implementing this model for correlated time-series outputs.
- The STAN code developed by Spence *et al.* (2018) to build a general framework for combining ecosystem models has been transferred to an R package.
- The package integrates outputs of multispecies/ecosystem models reflecting a common metric (best guess estimates; can be an abundance or ecosystem indicators) and fitted on unperfect observed data to estimate a common agreement of the models about the relative changes in the metric. Along with this common agreement are also estimated model-specific discrepancies (deviation from the agreement; both long- and short-term), common agreement discrepancies (deviation from the truth; both long- and short-term), and uncertainty around the common agreement estimate.
- The hindcast part is followed by a forecast in which the estimated discrepancies are used together with the projections from the ecosystem models to predict future changes in the metric and associated uncertainties.
- The package is applied to the outputs of four multispecies models (EwE, FishSUMS, LeMans, mizer) reflecting the biomass of four exploited species of the North Sea (sandeel, herring, cod, sole). This case study serves as a base for the documentation of the package.
- The package provides a set of functions to elicit the Bayesian priors, run the model, graphically represent its outputs and facilitate self-code and modify the model in STAN.

Spence, Michael A., Julia L. Blanchard, Axel G. Rossberg, Michael R. Heath, Johanna J. Heymans, Steven Mackinson, Natalia Serpetti, Douglas C. Speirs, Robert B. Thorpe, and Paul G. Blackwell. "A general framework for combining ecosystem models." Fish and Fisheries 19, no. 6 (2018): 1031-1042.

Can we simultaneously adopt a precautionary approach for all fish?: a case study in the North Sea (contributed by Michael Spence, James Martindale, Kahtija Allijii, Hayley J. Bannister, Robert B. Thorpe, Nicola D. Walker and Peter Mitchell)

- Part of the aim of managing fisheries is to adopt the precautionary approach. Typically the precautionary approach is defined on a species by species basis where biological interactions between different species are ignored. This talk investigated whether 9 species in the North Sea could be deemed precautionary, where "the probability that the long-term SSB > Blim is greater than 0.95", simultaneously.
- An ensemble of 4 North Sea multispecies models (EwE, LeMans, mizer, FishSUMS) were used to explore the effect of different fishing mortality rates for 9 species (sandeel, norway pout, herring, whiting, sole, plaice, haddock, code, saithe) on the abundance of each other. The model outputs were integrated in the ensemble modelling framework developed by Spence *et al.* (2018).
- For multiple combinations of fishing mortality values for the 9 species, the ensemble modelling framework projects the change in the later species abundance up to 2050, with associated uncertainty.
- Using the reference point provided in the stock assessments, the ensemble model projections of all runs are analyzed to determine whether each species meets the single-species precautionary approach criterion (value of F for which probability that SSB < Blim is less than 5%).
- If the zero-fishing scenario doesn't satisfy the precautionary approach, several multi-species fishing strategies can be identified, with associated uncertainty, to provide multispecies advice.
- Using the ensemble model developed in Spence *et al.* (2018), probability was robustly calculated and the space where all nine species were simultaneously precautionary. For some species, e.g. cod, some fishing was required, else others would not be in a precautionary state.

Spence, Michael A., Khatija Alliji, Hayley J. Bannister, Nicola D. Walker, and Angela Muench. [preprint, note title differs on arXiv preprint] Models, like fish, should not be treated in isolation: Using an ensemble model to calculate multispecies maximum sustainable yield" . arXiv preprint arXiv:2005.02001 (2020).

A multi-model study about the sensitivity of indicators to fishing pressure (contributed by Michael Spence)

- This approach uses the ensemble modelling framework developed by Spence *et al.* (2018) to quantify the response of the global status of the ecosystem
- An ensemble of 5 North Sea multispecies models (EwE, LeMans, mizer, FishSUMS, StrathE2E) were used to explore the effect of different single- or multi-species fisheries management scenarios (MSY, Nash, No fishing, Status Quo) on seven ecosystem indicators reflecting the total ecosystem biomass, the size-based structure of the communities or populations (mean maximum mean length, large fish indicator, typical length), top predator abundance (total biomass of birds and mammals), and low trophic level abundance (zooplankton abundance) and dynamics (zooplankton/phytoplankton biomass ratio).
- The ensemble modelling framework provides one forecast per indicator resulting from the combination of all ecosystem/multispecies models.
- The indicators affected the most by the fisheries pressure scenarios are those based on size. Those relative to top predators or low trophic levels are not conclusive enough.

- The hindcast part from the ensemble modelling allows characterization of the model skill for estimating each indicator. Here, as might be expected, the most reliable models are the size-based models when they are used to estimate length-related indicators.

Comparing qualitative and quantitative foodweb models (contributed by Sean Lucey)

- The utility of qualitative models compared to quantitative models was explored using a foodweb model of the Gulf of Maine and Western Scotian Shelf parameterized in Rpath (Lucey *et al.* 2020) and QPress (Melbourne-Thomas *et al.* 2012).
- A community matrix was created from Rpath by summing positive and negative consumption rates.
- A series of qualitative models were created systematically removing weaker links in the community matrix to represent versions of the network with varying degrees of knowledge from all interactions to only strong interactions.
- Several perturbations were run and compared using the outputs from QPress and Mixed Trophic Interactions (MTI) in Rpath.
- Initial results were inconclusive so the authors are looking to expand by using the ecosense routine within Rpath to generate more comparable outputs to QPress.

Lucey, S. M., Gaichas, S. K., & Aydin, K. Y. (2020). Conducting reproducible ecosystem modelling using the open source mass balance model Rpath. Ecological Modelling, 427, 109057.

Melbourne-Thomas, J., Wotherspoon, S., Raymond, B., and Constable,A. 2012. Comprehensive evaluation of model uncertainty in qualitative network analyses. Ecological Monographs, 82: 505–519.

Within model ensembles with Rpath (contributed by Sean Lucey)

- New RPath model of Georges Bank was parameterized using recent survey data.
- Not enough data points were available to fit to so the model was run through the ecosense routine in Rpath with generated ~1000 parameter sets.
- This set of models was further reduced by looking at the performance relative to a specific question and targeting biomass and landings to be within two-fold of their current values. This reduces the number of models to about 300.
- Still work to be done to investigate which parameters are sensitive and to compare to a fully fitted model.

Lucey, S. M., Gaichas, S. K., & Aydin, K. Y. (2020). Conducting reproducible ecosystem modelling using the open source mass balance model Rpath. Ecological Modelling, 427, 109057.

WKIRISH: Multispecies modelling and the advice process: lessons from an 8-stock fish community model for the Irish Sea (contributed by Robert Thorpe, Michael Spence, Paul Dolder, and Richard Nash)

- This work fits a LeMANS multispecies size structured model for 8 species in the Irish Sea. Advantages of LeMANS include ability to represent size structure, the use of life history traits to parameterize species' responses, and reproducible predictions (via the R-package). Parameter uncertainties can be quantified using MCMC methods.
- The model was fit to a variety of fishery-dependent and fishery-independent data.
- The model estimates that natural mortality on all stocks has increased over time, even though recovery of stock biomasses has been patchy. This is probably due to changes in the environment that are unfavourable for stock productivity.
- The model estimates significant mortality for age 5+ cod. This might be due to emigration of mature cod from the Irish Sea or poor environmental conditions, and was discussed as an issue at WKIRISH.
- Overall, seven out of eight stocks did not fit well to all sources of data simultaneously, illustrating the challenges of fitting multispecies models.
- From a tools standpoint, advantages of the model framework include availability on CRAN and github, and fast estimation (a couple hours) using TMB. However uncertainty quantification via MCMC is laborious and slow.
- Note that the model fitting procedure used a 'Get Fit Quick' toolbox (Spence, CEFAS, ToR C), that may be useful for other model types within WGSAM.

Spence, M. A., Dolder, P. J., Nash, R., & Thorpe, R. B. (2021). The Use of a Length-Structured Multispecies Model Fitted Directly to Data in Near-Real Time as a Viable Tool for Advice. Frontiers in Marine Science, 1373.

Annex 6: ToR E

MSE: Management Strategy Evaluation (MSE) methods and applications for multispecies and ecosystem advice, including evaluating management procedures and estimating biological reference points

Nash equilibrium R package to get reference points for any ecosystem model, and how to adequately get the message of multispecies models across for decision makers (contributed by Thomas Del Santo O'Neil, Axel G. Rossberg, Robert Thorpe)

- The method aims to make the diagnosis of reference points from multispecies models more impactful, to enhance the consideration of such models in fisheries advice.
- This approach relies on the convex-hull graphs (delimited by the so-called Pareto frontier) drawn from multispecies model simulations that represent all the possible combinations of yields from one species consistent with a prescribed yield of the other between two species.
- An R package called Nash has been developed to integrate multispecies model outputs and perform an algorithm to determine the Nash equilibrium.
- Instead of providing the classical convex-hull graphs on which are plotted the multispecies yield optima, this approach proposes synthetic indicators of interaction strength between the exploitation of pairs of species. This information is summarized as a simplified network graph that can be reduced to the stronger interactions.
- To illustrate the functioning of the framework, this approach is applied to outputs of the Ecopath with Ecosim models of the Baltic Sea and the North Sea.
- The R package can be directly connected to code-based ecosystem frameworks. In the application case, the Nash package is connected to Rpath (Lucey *et al.*, 2020).

Nash R package (Contact: Thomas Del Santo O'Neil)

Lucey, S. M., Gaichas, S. K., & Aydin, K. Y. (2020). Conducting reproducible ecosystem modelling using the open source mass balance model Rpath. Ecological Modelling, 427, 109057.

Lucey, S. M., Aydin, K. Y., Gaichas, S. K., Cadrin, S. X., Fay, G., Fogarty, M. J., and Punt, A. (2021). Evaluating fishery management strategies using an ecosystem model as an operating model. Fisheries Research, 234: 105780