Journal of Northwest Atlantic Fishery Science

Volume 57 • Special Issue • 2026

Applying the Ecosystem Approach to Fisheries Management in ABNJ Symposium

11–13 March 2025 • FAO Headquarters • Rome, Italy

Posted online 11 September 2026

Northwest Atlantic Fisheries Organization
1601 Lower Water Street, Suite 401, Halifax, Nova Scotia, B3J 3P6 Canada
Tel.: +1 (902) 468–5590
Email: journal@nafo.int • Website: https://journal.nafo.int • www.nafo.int

ISSN: 0250-4408
E-ISSN: 1813-1859

Contents

Journal of Northwest Atlantic Fishery Science

Scientific publications by the International Commission for the Northwest Atlantic Fisheries (ICNAF) and the Northwest Atlantic Fisheries Organization (NAFO) have been in existence since ICNAF began in 1949 with the ICNAF Special Publication series dealing with proceedings of scientific symposia. The ICNAF Research Bulletin was started in 1964 to provide a means of publishing results of scientific research relevant to ICNAF. The *ICNAF Research Bulletin* was terminated in September 1979 after the issue of Number 14. The first volume of the NAFO *Journal of Northwest Atlantic Fishery Science* was published in December 1980, after NAFO came into force replacing ICNAF in 1979.

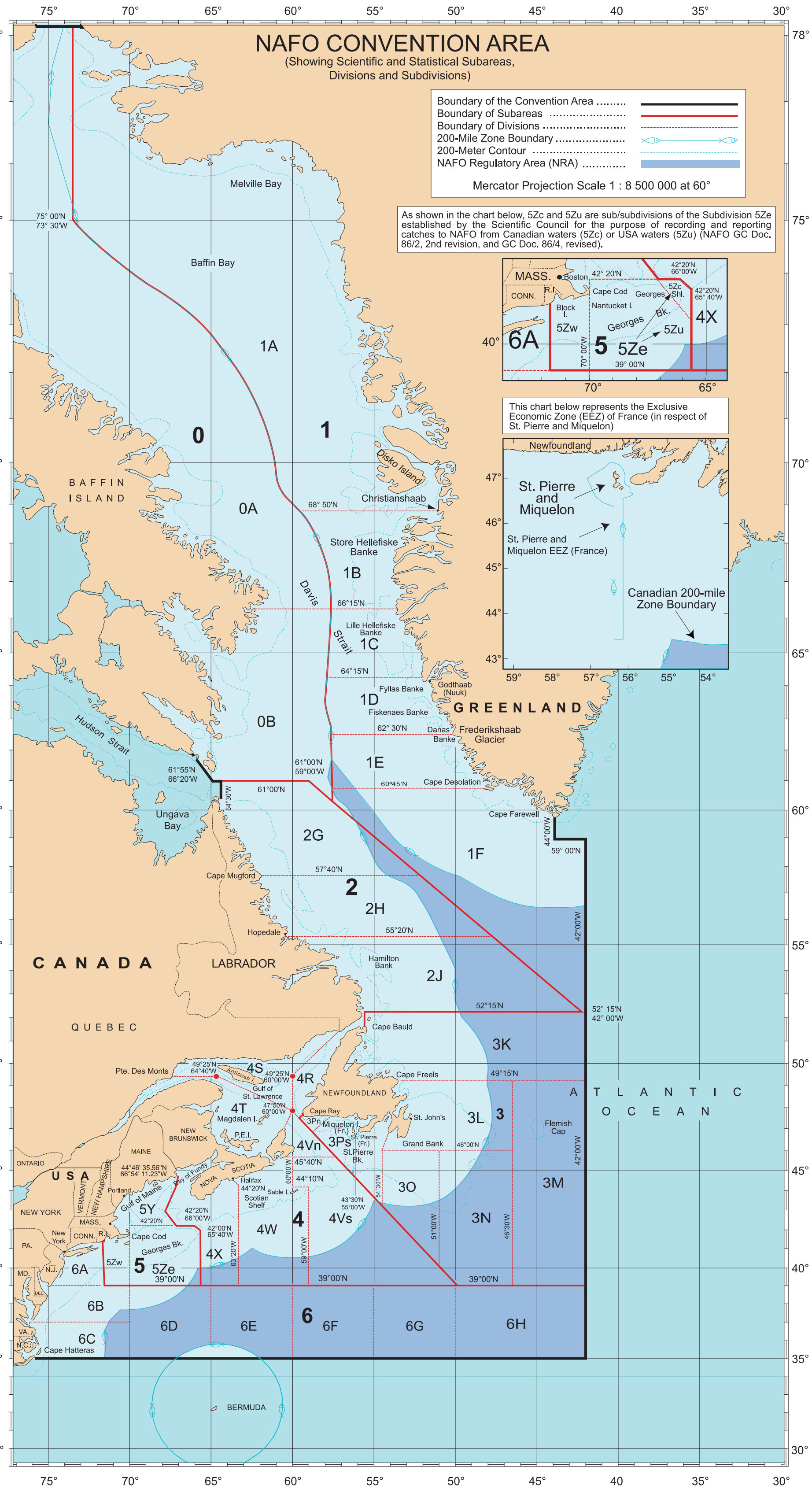
The Northwest Atlantic fisheries have a rich history, and a great deal of research has been sponsored and encouraged by NAFO and its predecessor ICNAF. NAFO has been a leader amongst international organizations in the application of science to fishery management and in the regulation of fisheries in areas beyond national jurisdiction. The Scientific Council of NAFO publishes the *Journal of Northwest Atlantic Fishery Science*, which contains peer-reviewed primary papers. Lists of these and other NAFO publications are given on the back of this issue.

Editorial Policy

The Journal provides an international forum for the primary publication of original research papers, with emphasis on environmental, biological, economic and social science aspects of fisheries and their interactions with marine habitats and ecosystems. While the Journal is intended to be regional in scope, papers of general applicability, and methodological and review papers are considered. Space is available for notes and letters to the editor to facilitate scientific discussion of published papers. Both practical and theoretical papers are eligible. All papers are peer-reviewed to determine their suitability for primary publication. Associate Editors arrange for the peer-reviews and ensure that the papers accepted for publication meet the high standards required for the Journal. Manuscripts approved for publication are accepted with the understanding that they are not copyrighted, published or submitted elsewhere except in abstract form. There are no page charges.

Editorial Board

The Scientific Council of NAFO publishes the *Journal of Northwest Atlantic Fishery Science*, containing peer-reviewed primary literature detailing original research of relevance to fisheries science and management in the Northwest Atlantic Ocean. Articles are published electronically under a Creative Commons Attribution-Non Commercial 4.0 International and https://creativecommons.org/licenses/by-nc/4.0/, and are freely available at https://journal.nafo.int. NAFO Scientific Council has resolved to produce annual or bi-annual online volumes and these represent a compilation of the web based articles published throughout the year. Additionally, the journal supports the use of digital object identifiers (DOIs) for electronic media and encourages others to support this initiative. The citations are now downloadable to various reference software platforms. The journal is indexed in the Aquatic Sciences Fisheries Abstract (ASFA) database, Elsevier, EBSCO, Google Scholar, and SCOPUS.



NAFO CONVENTION AREA
(Showing Scientific and Statistical Subareas, Divisions and Subdivisions)
Boundary of the Convention Area
Boundary of Subareas
Boundary of Divisions
200-Mile Zone Boundary
200-Meter Contour
NAFO Regulatory Area (NRA)
Mercator Projection Scale 1 : 8 500 000 at 60°
As shown in the chart below, 5Zc and 5Zu are sub/subdivisions of the Subdivision 5Ze established by the Scientific Council for the purpose of recording and reporting catches to NAFO from Canadian waters (5Zc) or USA waters (5Zu) (NAFO GC Doc. 86/2, 2nd revision, and GC Doc. 86/4, revised).
This chart below represents the Exclusive Economic Zone (EEZ) of France (in respect of St. Pierre and Miquelon)
St. Pierre and Miquelon
St. Pierre and Miquelon EEZ (France)
Canadian 200-mile Zone Boundary
Newfoundland
CANADA
GREENLAND
BAFFIN ISLAND
LABRADOR
QUEBEC
NEWFOUNDLAND
USA
ATLANTIC OCEAN
Melville Bay
Baffin Bay
Davis Strait
Hudson Strait
Ungava Bay
Disko Island
Christianshaab
Store Hellefiske Banke
Lille Hellefiske Banke
Fyllas Banke
Fiskenaes Banke
Danas Banke
Godthaab (Nuuk)
Frederikshaab Glacier
Cape Desolation
Cape Farewell
Cape Mugford
Hopedale
Hamilton Bank
Cape Bauld
Cape Freels
St. John's
Grand Bank
Flemish Cap
Gulf of St. Lawrence
Anticosti I.
Pte. Des Monts
Magdalen I.
Cape Ray
Miquelon I. (Fr.)
St. Pierre (Fr.)
St.Pierre Bk.
Halifax
Sable I.
Scotian Shelf
Bay of Fundy
Gulf of Maine
Portland
Boston
Cape Cod
Nantucket I.
Block I.
Georges Bk.
Georges Shl.
New York
Cape Hatteras
BERMUDA
0 0A 0B 1 1A 1B 1C 1D 1E 1F 2 2G 2H 2J 3 3K 3L 3M 3N 3O 3Ps 3Pn 4 4R 4S 4T 4Vn 4Vs 4W 4X 5 5Y 5Ze 5Zw 5Zc 5Zu 6 6A 6B 6C 6D 6E 6F 6G 6H
75° 00'N 73° 30'W
68° 50'N
66°15'N
64°15'N
62° 30'N
60°45'N
61°00'N 59°00'W
61°55'N 66°20'W
61°00'N
64°30'W
59° 00'N
44°00'W
57°40'N
55°20'N
52°15'N
52° 15'N 42° 00'W
42°00'W
49°15'N
49°25'N 64°40'W
49°25'N 60°00'W
47°50'N 60°00'W
46°00'N
45°40'N
44°10'N
43°30'N 55°00'W
54°30'W
51°00'W
46°30'W
44°46' 35.56"N 66°54' 11.23"W
42°20'N 66°00'W
42°20'N
42°00'N 65°40'W
63°20'W
59°00'W
60°00'W
39°00'N
42° 20'N
70° 00'W
39° 00'N
42°20'N 65° 40'W
MASS. CONN. R.I. VERMONT NEW HAMPSHIRE MAINE NEW BRUNSWICK NOVA SCOTIA P.E.I. ONTARIO NEW YORK PA. N.J. MD. DEL. VA. N.C.
June 2015

Special Issue from the Symposium on Applying the EAFM in ABNJ

This special issue of the Journal of Northwest Atlantic Fishery Science follows from the symposium "Applying the Ecosystem Approach to Fisheries Management in ABNJ," held from 11–13 March 2025, at the Food and Agriculture Organization of the United Nations (FAO) Headquarters in Rome, Italy. The symposium, organized in collaboration with the FAO, Northwest Atlantic Fisheries Organization (NAFO) and the International Council for the Exploration of the Sea (ICES), convened an interdisciplinary community of scientists, policymakers, legal scholars, representatives of regional fisheries management organizations (RFMOs), and other stakeholders, with the aim of advancing both understanding and practical implementation of ecosystem approach to fisheries management (EAFM) in areas beyond national jurisdiction (ABNJ). The symposium was organized into three thematic days relevant to science, management and implementation guidance.

Science to Support EAFM

The first thematic stream of the symposium focused on the scientific underpinnings that support an EAFM. Presentations in this session covered three broad topics. The first focused on retained species, including research on the associated ecological impacts of their removals, using logbook and VMS data to better understand the bottom fishing footprint in the NAFO Regulatory Area, and the links between changes in ocean climate and fish productivity in the Northwest Atlantic. Secondly, research on discarded and vulnerable species was presented, including methods and challenges for identifying vulnerable marine ecosystems from a South Pacific Regional Fisheries Management Organisation (SPRFMO) perspective, actions to monitor and mitigate bycatch in the Mediterranean and Black Sea, and recent steps towards incorporating assessment of impacts to vulnerable and discarded bycatch species into ecosystem-based management of fisheries in the North Pacific Fisheries Commission (NPFC) Convention area. Finally, ecosystem effects and spatial management research were discussed, including setting thresholds for good ecosystem state in marine seabed systems, exploring how connectivity affects the EAFM and implementing the ecosystem approach in the Southern Indian Ocean Fisheries Agreement (SIOFA).

Science-management interface and management

The second theme addressed the interface between scientific knowledge and fisheries management and covered three broad topics. First, managers shared their experiences implementing an EAFM, drawing on perspectives from a range of RFMOs and other governing bodies. Second, the challenge of reconciling sustainable harvest with biodiversity conservation was explored through case studies on implementing an EAFM in the Mediterranean and Black Sea, trade-offs between fishing opportunities and Vulnerable Marine Ecosystem (VME) fishery closures, the ICES experience in assessing and communicating spatial uncertainty, and dialogue and participatory processes at the science–management interface from a NAFO perspective. Finally, discussions focused on EAFM in tuna fisheries, highlighting both the progress made and the challenges remaining in implementing and operationalizing EAFM across tuna RFMOs.

Implementation, Tools, and Future Directions

The third thematic stream focused on the practical implementation of EAFM in ABNJ and the development of forward-looking guidance. Presentations showcased decision-support tools, ecosystem indicators, and risk assessment frameworks designed to support management in both data-rich and data-limited contexts. Speakers also addressed the integration of socioeconomic considerations, stakeholder engagement and the application of area-based management measures. Broader discussions considered alignment with global biodiversity initiatives and emerging governance approaches, such as ecoregional management. Across sessions, there was strong emphasis on the need for actionable guidance, adaptive management, and enhanced institutional coordination.

Special Issue Contributions

The contributions to this special issue reflect the breadth of topics and discussions that evolved during the symposium. In scientific support of an EAFM, Regular *et al.* (2026) present a novel state-space multispecies production model that accounts for species interactions and environmental effects and was shown to be a promising avenue for producing more holistic and accurate assessments for multiple species with relatively minimal data requirements. Kenchington (2026) provides an overview of how NAFO has incorporated information on ecological connectivity, a key property of marine ecosystems operating across multiple spatial scales, into its decision-making processes.

At the science-management interface, Thompson *et al.* (2026) review the incorporation of the ecosystem approach to fisheries in international law, existing guidance supporting its implementation, and the achievements and remaining challenges associated with implementing the approach within RFMOs responsible for deep-sea fisheries. Complementing this perspective, Campbell (2026) synthesizes lessons on communicating uncertainty in scientific advice, focusing on VMEs, by drawing on experiences from RFMOs and other deep-sea management jurisdictions to provide practical guidance for scientists and managers navigating the interface between research and policy implementation. The implementation of EAFM by different governing bodies is further illustrated through case studies. Tablada *et al.* (2026) describe the development and application of the SPRFMO Bottom Fishery Impact Assessment Standard and Encounter Review Standard, highlighting practical approaches to operationalizing EAFM within deep-sea fisheries management, Milardi (2026) traces SIOFA's pragmatic journey in operationalizing EAFM, including the SIOFA Ecosystem Summary, while Savalny *et al.* (2026) provide examples of ICES integration of ecosystem information into advice, including the Ecosystem Advised F, the regional benthic impact assessments and trade-off analysis and the ICES Framework for Ecosystem-Informed Science and Advice.

In bringing together these contributions, this special issue provides an assessment, past, present and forward-looking, of the state of EAFM in ABNJ. It serves both as a record of the symposium and as a platform for continued dialogue among researchers and practitioners committed to sustainable ocean governance.

J. Northw. Atl. Fish. Sci., Vol. 57, Special Issue: 1–15 Publication (Upload) date: 11 Sep. 2026
Conference article

Summing the Parts: Improving Population Estimates Using a State-space Multispecies Production Model

Paul M. Regular*, Mariano Koen-Alonso, M. Joanne Morgan, Pierre Pepin†, Rick M. Rideout
Fisheries and Oceans Canada, Northwest Atlantic Fisheries Centre, 80 East White Hills, St. John's, Newfoundland and Labrador, A1C 5X1, Canada

*Corresponding author; E-mail: Paul.Regular@dfo-mpo.gc.ca
†Current address; Three Dog House, 1023 Indian Meal Line, Portugal Cove - St. Philip's, Newfoundland and Labrador, A1M 3C4, Canada

Regular, P.M., Koen-Alonso, M., Morgan, M.J., Pepin, P., and Rideout, R.M. 2026. Summing the parts: Improving population estimates using a state-space multispecies production model. *J. Northw. Atl. Fish. Sci.*, **57(2)**: 1–15. https://doi.org/10.2960/J.v57.m750

Abstract

Carrying capacity is a fundamental concept in ecology that has inspired the development and application of a broad range of population models. In the context of fisheries science, production models have been employed globally to calculate carrying capacity and guide the sustainable use of fish populations. Production models have, however, been criticized for failing to account for species interactions and environmental effects. We aim to fill some of these gaps by introducing a novel state-space multispecies production model. We apply our extended model to commercially important demersal fish species off the east coast of Canada to assess its ability to reveal species interactions and the relative impacts of fishing and environmental effects. Our results indicate that accounting for species interactions increases the accuracy of biomass estimates for species within a community. The model also revealed strongly correlated process deviations, unrelated to fishing or density-dependent effects, which unexpectedly indicates that widespread collapses were primarily driven by a common environmental driver rather than fishing. Such inferences indicate that this may be a promising avenue for producing more holistic and accurate assessments for multiple species with relatively minimal data requirements (time-series of landings and fisheries-independent indices). Finally, this approach may serve as a stepping stone towards an ecosystem-based approach to fisheries management.

Keywords: Multispecies production model, State-space framework, Ecosystem-based fisheries management, Demersal fish populations, Environmental drivers

Introduction

The concept of carrying capacity has long been foundational in applied population ecology, being widely used in the management of renewable resources (Chapman and Byron, 2018; Hilborn *et al.*, 1995). The understanding that populations produce more offspring than an environment can sustain led to the notion that the 'surplus' can be harvested sustainably (Pauly and Froese, 2021). These ideas are exemplified by the concept of maximum sustainable yield (MSY) in the classic single-species surplus production modeling framework (Schaefer, 1954). In one equation, this framework attempts to explain interannual changes in biomass using fisheries landings and estimates of intrinsic growth rate and carrying capacity. Given the theoretical elegance of the approach, it has been both widely adopted and scrutinized. Estimates of carrying capacity, and resultant derivations of MSY, are frequently criticized for being time-invariant, which ignores the ubiquity of environmental variation (Del Monte-Luna *et al.*, 2004). Moreover, traditional surplus production models tend to focus on single-species dynamics and often disregard the complexities arising from species interactions within ecosystems (Gamble and Link, 2009).

Recognizing the limitations of single-species approaches, there have been calls to move towards an ecosystem-based approach to fisheries management (EBFM; Latour *et al.*, 2003). EBFM acknowledges the intricate web of ecological interactions and aims to ensure the sustainability and integrity of marine ecosystems while supporting viable fisheries (Pikitch *et al.*, 2004). To successfully implement EBFM, it is crucial to develop models that account for species interactions and the dynamics of multiple species within the ecosystem. Substantial progress has been made in the development of multispecies models and a spectrum of approaches have been developed, ranging from complex models that attempt to account for all parts of marine ecosystems (*e.g.*, Fulton *et al.*, 2011) to multispecies age-structured assessment models (*e.g.*, Albertsen *et al.*, 2018) to multispecies surplus production models (*e.g.*, Bundy *et al.*, 2012; Gamble and Link, 2009; Mueter and Megrey, 2006). However, application of these approaches to fisheries management have often been hindered by data limitations (*e.g.*, age data are frequently not available) and knowledge gaps (*e.g.*, incomplete understanding of food-web interactions). There is therefore a need for methods to help bridge the gap between single-species and multispecies assessment in data or information poor circumstances.

In this paper, we borrow concepts from single-species surplus production modeling (Millar and Meyer, 2000) and multispecies modeling (Albertsen *et al.*, 2018) to construct a model that incorporates the impacts of fishing on single-species populations and accounts for species interactions within the ecosystem. The data requirements of this model are relatively minimal, requiring species-specific landings and survey indices of biomass. As a case study, we apply this model to commercially important demersal fish species off the east coast of Canada, specifically the Grand Banks of Newfoundland. This case study is particularly germane due to the widespread collapse of most stocks in the area during the early 1990s (Lear, 1998), leaving the relative contributions of fishing and environmental impacts uncertain (Pedersen *et al.*, 2017). Using this case study, we aim to reveal species interactions, distinguish the impacts of fishing from environmental effects, and demonstrate the utility of this modeling approach. The subsequent sections of this paper will present the conceptual framework of our model, describe its application, and discuss the implications of our findings for ecosystem-based fisheries management.

Methods

Model formulation

Trends in fish populations have frequently been described using state-space production models of the form

$$B_y = \left(B_{y-1} + g(B_{y-1}) - C_{y-1}\right)e^{\delta_y}, \quad (1)$$

$$I_{y,i} = q_i B_y e^{\varepsilon_{y,i}}, \quad (2)$$

where B_y is biomass at the start of year y, C_y is the catch through year y, $g(B)$ is production as a function of biomass, $I_{y,s}$ is an index of relative abundance in year y from survey i, q_i is the time-invariant catchability coefficient for survey index i, δ is process error, and ε is observation error. Statistical challenges aside, the most difficult aspect of this model to parameterize is the production function as it needs to capture changes caused by growth, recruitment, and natural mortality. Schaefer (1954) proposed a solution by applying the logistic equation to describe self-limiting growth,

$$g(B) = rB\left(1-\frac{B}{K}\right), \quad (3)$$

where r is the maximum per-capita rate of change and K is the carrying capacity. That is, a populations' intrinsic ability to grow (rB) is limited by the size of the current population relative to the maximum biomass the system can support ($1 - B/K$). While this formulation offers an elegant description of single-species population dynamics, it assumes that density-dependent effects are solely caused by intraspecific competition and ignores the potential effects of other species inhabiting the same ecological area, competing for the same resources. We present an extension of equation (3) that models the growth of a focal species s while accounting for intra- and interspecific competition. Here, density-dependent effects are incurred when the total biomass of all species, indexed by s', exceeds the capacity of the system, K_Σ,

$$g_s(B_s) = r_s B_s\left(1 - \frac{\sum_{s'=1}^{S} B_{s'}}{K_\Sigma}\right). \quad (4)$$

While intrinsic rates of growth may vary across species, this formulation implies that the growth of all species is ultimately limited by the finite amount of energy in a region (*i.e.*, as the total population of all species in the system increases towards K_Σ, year-over-year growth of all species slows). Combining equations (1), (2), and (4), our model becomes

$$B_{y,s} = \left(B_{y-1,s} + r_s B_{y-1,s}\left(1 - \frac{\sum_{s'=1}^{S} B_{y-1,s'}}{K_\Sigma}\right) - C_{y-1,s}\right)e^{\delta_{y,s}}, \quad (5)$$

$$I_{y,i,s} = q_{i,s} B_{y,s} e^{\varepsilon_{y,i,s}}. \quad (6)$$

One simplifying assumption of this formulation is that each unit of biomass, regardless of species, contributes equally to limiting the realized growth of any given species. This assumption is partially relaxed through the covariance structure, which allows positive or negative associations among species beyond the shared carrying capacity. Though such associations may arise from the observation process, we assume that most covariance stems from ecosystem processes. We therefore treat observation errors as independent and normally distributed deviations such that $\varepsilon_{y,i,s} \sim N(0, \tau_{i,s})$, where the standard deviation parameter $\tau_{i,s}$ represents species- and survey-specific levels of observation error.

To account for temporal dependencies driven by ecological processes, a more flexible error structure is used to describe the process errors. Species interactions may drive positive or negative population responses resulting from direct or indirect associations. Deviations from expected production may also display temporal dependence if the factors contributing to the process errors change gradually over time. Such inertia may cause positive or negative process errors to persist over several years. A first-order autoregressive (AR1) process was therefore applied to account for temporal dependence. Both sources of dependence are modeled using a multivariate AR1 process where

$$
\begin{aligned}
\boldsymbol{\delta}_1 &\sim N(0, \boldsymbol{\Sigma}) \\
\boldsymbol{\delta}_2 &= \phi \boldsymbol{\delta}_1 + \boldsymbol{\varepsilon}_2, \quad \boldsymbol{\varepsilon}_2 \sim N(0, \boldsymbol{\Sigma}) \\
\boldsymbol{\delta}_y &= \phi \boldsymbol{\delta}_{y-1} + \boldsymbol{\varepsilon}_y, \quad \boldsymbol{\varepsilon}_y \sim N(0, \boldsymbol{\Sigma}), \; y = 3, \ldots, Y
\end{aligned} \tag{7}
$$

Here $\boldsymbol{\delta}_y = (\delta_{y,1}, \ldots, \delta_{y,S})^{\top}$ is the vector of process deviations across species. The parameter ϕ controls temporal autocorrelation, where values near 0 indicate weak persistence and values near 1 indicate strong persistence. Although different species may exhibit different levels of temporal correlation, a single ϕ is assumed to avoid over-parameterization. Nevertheless, effective differences in temporal correlation among species can still emerge through the covariance matrix $\boldsymbol{\Sigma}$, which captures cross-species dependence:

$$
\boldsymbol{\Sigma} = \begin{bmatrix} \sigma_1^2 & \sigma_1 \sigma_2 \rho_{1,2} & \cdots & \sigma_1 \sigma_S \rho_{1,S} \\ \sigma_2 \sigma_1 \rho_{2,1} & \sigma_2^2 & \cdots & \sigma_2 \sigma_S \rho_{2,S} \\ \vdots & \vdots & \ddots & \vdots \\ \sigma_S \sigma_1 \rho_{S,1} & \sigma_S \sigma_2 \rho_{S,2} & \cdots & \sigma_S^2 \end{bmatrix}. \tag{8}
$$

Species-to-species correlations are described by $\rho_{s,s'}$ ($s \neq s'$), with values between -1 and 1 representing negative to positive association. This flexible structure allows the testing of alternative hypotheses that process errors are independent through time or across species ($\phi = 0$ or $\rho_{s,s'} = 0$). The possibility that process errors are similarly correlated across all species may also be tested by estimating only one ρ parameter. Finally, the magnitude of the process error deviations is controlled by the species-specific standard deviation parameters, σ_s.

In implementation, $\boldsymbol{\Sigma}$ is parameterized as $\mathbf{DRD}$, where $\mathbf{D} = \mathrm{diag}(\sigma_1, \ldots, \sigma_S)$ and $\mathbf{R} = \mathbf{L}\mathbf{L}^{\top}$ is a correlation matrix obtained from a Cholesky factor $\mathbf{L}$ constructed from unconstrained parameters. This formulation ensures that $\boldsymbol{\Sigma}$ is positive definite.

Minor extensions of the formulation also permit the fitting of covariates which may describe an underlying linear effect. Two options were implemented, one that affects the process errors by substituting $e^{\delta_{y,s}}$ in equation (5) with $e^{\beta_\delta X^{\delta}_{y,s} + \delta_{y,s}}$, and another that affects the carrying capacity by substituting K_Σ in equation (5) with $K_\Sigma e^{\beta_K X^K_y}$, where β parameters capture linear effects of covariates included in design matrices, X. The idea is that some factors may affect positive or negative changes in the populations while others may affect change in the total carrying capacity of the system. A covariate option for intrinsic rates of increase was not implemented since one goal of this model is to obtain estimates of this vital rate, which is not expected to change rapidly as it is shaped by natural selection (Hutchings, 2021). Equation (5) was also modified to enable the fitting of a single-species Schaefer production function by dropping the summation of biomass and estimating species-specific carrying capacities, K_s, rather than a system-level carrying capacity, K_Σ (*i.e.*, applying equation (3) separately to each species).

Statistical framework

This model was implemented using template model builder (TMB; Kristensen *et al.*, 2016), which is a R (R Core Team, 2021) package that enables the fitting of complex nonlinear random effects such as the latent B variable in state-space production models (equation (1)). Such variables are not directly measured but are inferred indirectly via observed values. Data fitting is accomplished using a combination of Laplace approximation and automatic differentiation to evaluate the joint likelihood (Kristensen *et al.*, 2016). Like the production model described by Pedersen *et al.* (2017), both frequentist and Bayesian inference of model parameters are possible. In development, we found that estimation of parameters was generally more successful when vaguely informative priors were specified, and in some cases, not estimable when unconstrained.

Case study

Data

The multispecies production model described above requires two basic inputs for each species: a time-series of catch ($C_{y,s}$ in equation (5)), and an index of population size ($I_{y,s}$ in equation (6)). The Northwest Atlantic Fisheries Organization (NAFO) and Fisheries and Oceans Canada (DFO) have been collecting and curating such information for multiple fish populations along the shelves of Newfoundland and Labrador (NL) since the 1970s. The communities inhabiting these shelves can be divided into several regions with distinct productivity *i.e.* ecosystem production units; Pepin *et al.* (2014). For our case study, we tallied catch data and calculated survey indices of multiple demersal fish populations from three regions (Fig. 1): 1) the Northeast NL Shelf (NAFO divisions 2J3K), 2) the Grand Bank (NAFO divisions 3LNO), and 3) Southern NL (NAFO sub-division 3Ps).

Catch data were extracted from NAFO's STATLANT 21A database (https://www.nafo.int/Data/STATLANT-21A, accessed 2022–01–21) and aggregated by region, species, and year. Survey indices were derived from the standardized, stratified random bottom-trawl surveys conducted each spring and fall by DFO; one of the largest fisheries-independent surveys in the world, covering more than 500 000 km² annually (roughly the size of Sweden or the Yukon, Canada) to depths up to 1 500 m. Since the inception of this program in 1971, survey platforms and protocols have undergone a series of changes that affect the continuity of the data collected in each region and season. A Yankee then Engel otter trawl, with nets designed to catch large demersal fish, were used from 1971 to 1994. Starting in the fall of 1995 survey gear was

Fig 1: Map of Newfoundland and Labrador (NL) case study area showing the Northeast NL Shelf (purple), Grand Bank (green), and Southern NL (yellow) ecosystem production units.

changed to a Campelen shrimp trawl with a small mesh codend, which allowed a broader range of species and size groups to be captured (Chadwick *et al.*, 2007). Within each era of the survey (Yankee, Engel, or Campelen) and for each season and region, samples used in this study were limited to strata that were sampled most years (> 80%) and to species found across more than 10% of these core strata. This often resulted in the exclusion of strata >750 m because these areas have been inconsistently sampled by the survey. Stratified analyses (Smith and Somerton, 1981) were then conducted on the remaining species to obtain indices of total biomass. To minimize bias introduced by inconsistent survey coverage, indices from years where more than 20% of the biomass was likely missed, inferred from time averaged percent occupancy within strata, were excluded from our analysis [*sensu* NAFO guidelines; page 10, NAFO (2019)]. Finally, species were ranked by cumulative commercial catch and limited to the seven most commonly caught species, or species group when catch was not consistently distinguished by species, within each region. On the Northeast NL Shelf, the included species were redfish spp. (*Sebastes fasciatus* and *Sebastes mentella* combined), wolffish spp. (*Anarhichas lupus* and *Anarhichas minor* combined), witch flounder (*Glyptocephalus cynoglossus*), American plaice (*Hippoglossoides platessoides*), Greenland halibut (*Reinhardtius hippoglossoides*), Atlantic cod (*Gadus morhua*), and skate spp. (*Amblyraja radiata* and *Malacoraja senta* combined). On the Grand Bank, the included species were redfish spp., yellowtail flounder (*Myzopsetta ferruginea*), American plaice, Greenland halibut, haddock (*Melanogrammus aeglefinus*), and Atlantic cod. Finally, along Southern NL, the species included were redfish spp., witch flounder, American plaice, white hake (*Urophycis tenuis*), haddock, Atlantic cod, and skate spp.

Priors

For simplicity, all priors were normally distributed and, in most cases, upper and lower inflection points ($\mu \pm \sigma$; ~68% of the total area under the curve) of each normal prior were defined using values in log or logit space. Upper and lower values were based on previous research or knowledge to impose fairly generic and vaguely informative priors. Interactive dashboards accompanying this paper provide visualizations of the priors and posteriors for core parameters (Supplement 1); here we summarize their parameterization and report the ranges used to define each prior.

Intrinsic growth rate, r_s, and carrying capacity, K

To capture a broad range of intrinsic growth rates (Thorson, 2020), 0.1 and 1 were chosen as the lower, r_l, and upper, r_u, values; this translates to a normal prior with a mean of -1.15 and a standard deviation of 1.15 on the log-scale. The log-scale K_Σ prior was informed by total levels of catch and r_l and r_u,

$$K_{\Sigma,l} = \frac{\max(\Sigma_s C_{y,s})}{r_u}, \quad K_{\Sigma,u} = \frac{4\max(\Sigma_s C_{y,s})}{r_l}, \quad (9)$$

where $K_{\Sigma,l}$ and $K_{\Sigma,u}$ are the lower and upper values. On the lower end, this prior imposes the assumption that the fishery is unlikely to have caught the equivalent of K_Σ and, on the upper end, it assumes that the maximum observed catch represents a portion of K_Σ (*sensu* Froese *et al.*, 2017). The division by the lower and upper values for r also accounts for the potential range of productivity. Note that the maximum time-series catches are species specific when estimating species-specific carrying capacities.

Starting biomass, $B_{1,s}$

Like K_Σ, catch was used to constrain the plausible range of the biomass at the beginning of the time series, $B_{1,s}$, which we will denote as $B0_s$ to simplify notation. Specifically,

$$B0_{l,s} = \frac{C_{1,s}}{r_u}, \quad B0_{u,s} = \frac{4C_{1,s}}{r_l}, \quad (10)$$

where $B0_{l,s}$ and $B0_{u,s}$ are the lower and upper values that are log transformed to define the normal prior for $\log(B0_s)$. Again, adjusting for the potential range of productivity from r_l to r_u, this assumes that the fishery did not catch all of the biomass in the first year and it assumes that the catch represents a portion of the biomass in the first year. A potential flaw with the upper value for this prior is that a lack of market demand may contradict the assumption that landings are coarsely proportional to stock size. However, the upper range chosen was considered reasonable for this case study as there was an active fishery for each species examined here at the start of the time series.

Process error variance, σ_s^2, temporal correlation, ϕ, and species-to-species correlation, $\rho_{s,s}$

Considerable process variability may arise from variable recruitment, natural mortality, and/or growth. For instance, species in the Scorpaenidae family, which includes the *Sebastes* genus, have notoriously variable recruitment which frequently results in "spasmodic" stock dynamics (Cadigan *et al.*, 2022; Licandeo *et al.*, 2020). Also, there is evidence that heightened and variable natural mortality contributed to the collapse and slow recovery of Atlantic cod along the Northeast NL Shelf (Cadigan, 2015; Regular *et al.*, 2022). To account for a wide range of possible standard deviations, σ_s, a vague prior with 0.01 and 1 as the lower and upper values were chosen. In log-space, this translates to a normal distribution with a mean of -2.3 and sd of 2.3.

There is little knowledge to determine the potential level of temporal or species-to-species dependence present in the focal systems; vague priors were therefore defined for ϕ and $\rho_{s,s}$. For ϕ, 0.1 and 0.9 were logit transformed $[\log(x/(1-x))]$ to define the upper and lower inflection points for a normal prior for the logit of ϕ. For ρ, the logit transformation was shifted $[\log((1+x)/(1-x))]$ to capture negative and positive lower (-0.9) and upper (0.9) values. When these parameters are estimated, these priors give most credence to moderate temporal correlation (0.5) and no species-to-species correlation (0) but still allow the possibility of high levels of correlation (0.9).

Catchability, $q_{i,s}$, and observation error variance, $\tau_{i,s}^2$

The catchability of the spring and fall surveys conducted by DFO likely changed over time given the shift in gear from a Yankee to Engel to Campelen trawl as well as spatial shifts in survey coverage of the strata in each region. Survey catchability $q_{i,s}$ is therefore indexed by season and gear, i, and species, s. Moreover, the lower inflection points for the $q_{i,s}$ priors were informed by the average survey coverage by gear and season. Survey coverage within each region was computed by dividing the average spatial coverage of strata across years by the total area of all strata (*i.e.*, average area covered / area of survey domain). To account for the fact that the proportion of a stock accessible to the survey may be lower than the nominal coverage, this ratio was further adjusted: multiplied by 0.2 for deep-water species (Greenland halibut, Atlantic halibut, witch flounder, redfish spp., white hake, silver hake, and monkfish) or by 0.5 for shallower shelf-associated species. These multipliers reflect prior expectations that gear selectivity (*e.g.*, escapement under the footgear; Walsh, 1992) reduces availability for all species, while deep-water species require an additional adjustment because a portion of the stock may occupy depths beyond the survey domain. The upper inflection point was set to 1 as it is possible that the survey indices represent overestimates of the true population size in some instances.

A prior for observation error variance was informed by unbiased design-based estimates of survey variance associated with annual biomass estimates (Smith and Somerton, 1981). These estimates were used to calculate the coefficient of variation (CV) for each survey, year, and species; specifically,

$$CV_{i,s,y} = \frac{\sqrt{Var(I_{i,s,y})}}{I_{i,s,y}} \quad (11),$$

where I represents the design-based indices of biomass used in equation (2). These CVs were log transformed and survey, i, and species, s, specific means and standard deviations were used to inform the prior for $\tau_{i,s}^2$ in log-space. Rather than treat the estimates of survey CV as a perfect indicator of total observation error, the prior was widened by multiplying the standard deviation of log CV by two to account for observation variance introduced by potential distributional shifts outside of the survey domain. Another two-time multiplier was applied for deep-water species because they have more scope for shifting outside the survey domain.

Model selection

The degree to which density-dependence of the demersal fish community inhabiting the NL shelves is driven by intra versus interspecific competition is unknown. Nor is the degree to which species interactions affect population dynamics. It is, however, well known that the community has been exploited for more than 500 years and this history was punctuated by a collapse of several stocks, most notably cod, in the early 1990s (Lear, 1998). This collapse was not isolated to commercial stocks, as the biomass of several non-commercial species collapsed at the same time. This was followed by a reorganization of the community, which implies that the system experienced a regime shift (Pedersen *et al.*, 2017). Given this context, and the structure of the multispecies surplus production model described above, a series of hypotheses were tested:

Full: For this hypothesis, it is posited that population dynamics within regions are governed by an overarching system-level carrying capacity that affects all focal species as the aggregate biomass approaches system limits (*i.e.*, inter-specific density-dependent effects are assumed). For this hypothesis and all others, annual reported landings of each species are accounted for in the production equation (5). Residual variations not explained by intrinsic growth, density-dependent effects or landings are described by process errors that are 1) correlated across species and said correlations are assumed to be unstructured, meaning relationships can be of differing strengths — positive, neutral, or negative — for each species-to-species pair; and 2) assumed to be temporally correlated, following an AR1 structure. Finally, a shift covariate was applied to the carrying capacity parameter to enable the estimation of different system limits before and after the community-wide collapse to assess support for a regime shift in each systems' capacity for the focal demersal species.

Just shift: Model structure is the same as the **full** model, except the process errors are assumed to be independent and identically distributed random variables (*iid*) to assess the hypothesis that temporal and species correlations are explained by the shift.

Just correlation: Model structure is the same as the **full** model, except population dynamics are assumed to be affected by a common and time-invariant carrying capacity. The shift covariate was not applied.

Shared correlation: Model structure is the same as the **just correlation** model, except species-by-species correlations in the process errors are assumed to be the same across all pairs. This structure implies that there is a common but unknown environmental variable affecting the population dynamics of all species. The shift covariate was not applied.

Just species correlation: Model structure is the same as the **shared correlation** model, except the process errors at each time step are assumed to be *iid*. This structure implies that there is a common but unknown environmental process affecting all species, but the process is noisy with no temporal dependence. The shift covariate was not applied.

Just temporal correlation: Model structure is the same as the **shared correlation** model, except species-by-species correlations are assumed to be *iid*. This structure implies that environmental processes affect each species differently, however, there may be carry-over effects from one year to the next. The shift covariate was not applied.

No correlation: Model structure is the same as the **shared correlation** model, except both temporal and species correlations are set to zero (*i.e.*, process innovations are *iid* across time and species). That is, population dynamics are thought to be affected by a common time-invariant carrying capacity and residual variations not explained by intrinsic growth, inter-specific density-dependent effects or landings are noisy and independent across time and species. The shift covariate was not applied.

Single-species: Model structure is the same as the **no correlation** model, except population dynamics are assumed to be governed by species-specific carrying capacities (*i.e.*, intra-specific density-dependent effects are assumed). This formulation is analogous to standard state-space Schaefer production models. The shift covariate was not applied.

The predictive ability of each of these models was tested using two cross-validation approaches: 1) leave-one-out cross-validation (LOO-CV), and 2) hindcast cross-validation (Hindcast-CV). LOO-CV is a form of exhaustive cross-validation where the model is repeatedly conditioned on a training set missing one observation (*i.e.*, one-fold) until the number of model folds equal the number of observations in the data. The missing observations are predicted at each fold, permitting assessments of the models' ability to predict the actual value that was left-out at each fold. The hindcast-CV approach is similar, but it focuses on the models' ability to predict the future. Under this approach, the model is repeatedly conditioned on a training set missing observations from the terminal year such that each fold excludes an increasing number of years worth of data from the tail of the time series (Kell *et al.*, 2016). We folded back 20 years and, for each fold, predicted survey indices were compared to the observed survey indices (*e.g.*, observed indices from 2020 were compared with predicted survey indices for 2020 from the model conditioned on data from 1978–2019). For both approaches, we denote predicted survey indices as $\widehat{I_j}$ and the left-out observations I_j, where j represents all unique combinations of years, species, and survey indices present in the left-out data. LOO-CV and Hindcast-CV prediction error scores for each model for each region were calculated by taking the mean squared error,

$$\text{CV Score} = \frac{1}{n}\sum_{j=1}^{n}\left(log(I_j) - log(\hat{I}_j)\right)^2 \quad (12).$$

These scores were also averaged across methods (LOO-CV, Hindcast-CV) and region (Northeast NL Shelf, Grand Bank, Southern NL) to obtain an overall score of predictive ability of each model. A well-fitting model will result in predicted values that are close to the excluded values and, therefore, result in lower scores. Ultimately, these scores enable a model-comparison approach to hypothesis testing. These scores are comparable even for the single-species model as it compares species-specific data points to predictions.

Code and Data Availability

All code used for the analyses in this study is publicly available in a research compendium on GitHub: https://github.com/PaulRegular/multispic. The compendium is organized as an R package, enabling straightforward replication of the results presented here and allowing the same methods to be applied to datasets from other regions.

Results

Both cross-validation metrics (LOO-CV and Hindcast-CV scores) indicate that most multispecies production model formulations outperform a single-species production model when applied to seven species within three ecosystem production units (Northeast NL Shelf, Grand Bank, and Southern NL) off the east coast of Canada (Fig. 2). Focusing on overall scores, the performance of the single-species production model was similar to a multispecies formulation that assumes there is no correlation in the process errors across species or time. There tends to be more notable decreases in the scores as temporal and species correlations are introduced, indicating an improvement in the predictive ability of these models. The "shared correlation" and "just correlation" formulations, in particular, tended to receive the lowest scores, and dropping the species and temporal correlations in lieu of a shift covariate ("just shift" formulation) resulted in a deterioration of predictive ability. Scores were improved when temporal and species-to-species correlations were introduced along with the shift covariate ("full" formulation); however, the fit of the "full" model tended to be poorer than the "just correlation" formulation, which further indicates that the "shift" covariate degraded the predictive ability of the model. Subsequent plots focus on the best fitting formulation, "just correlation", to demonstrate model predictions.

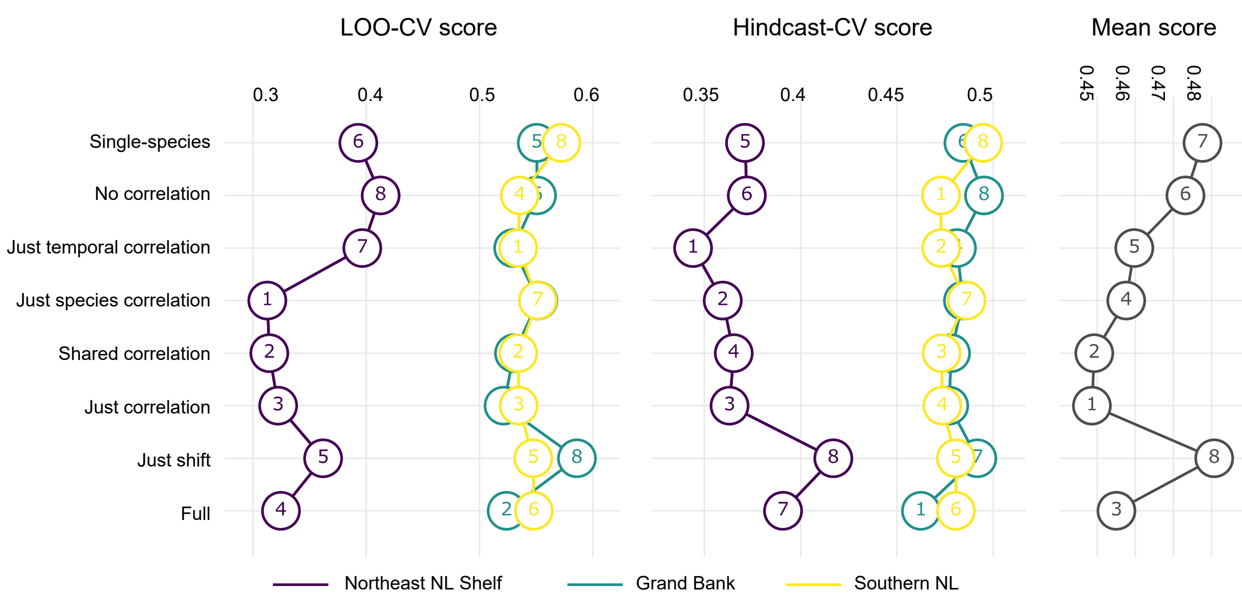


Fig. 2: LOO-CV and Hindcast-CV scores from a series of production model formulations of increasing complexity, from a single-species production model ("Single-species") to a multispecies production model with a covariate effect and species and temporal correlations ("Full"), fit to seven species in three ecosystem production units (Northeast NL Shelf, Grand Bank, and Southern NL) off the east coast of Canada. Overall scores for each model across score type and ecosystem production unit are shown on the rightmost facet.

The multispecies production model with unstructured species-to-species correlation and AR1 temporal correlation ("just correlation") offered an explanation of the trends in survey indices of focal species across three ecosystem production units with little signs of systematic bias (see residual plots included in model dashboards; Supplement 1). Predicted indices track observed values and, by estimating catchability parameters by species and survey, indices from temporally fragmented surveys are stitched together and their trends are used to inform a continuous underlying trend in biomass (Fig. 3). The earlier Yankee and Engel eras of the Canadian surveys tended to receive lower catchability estimates than the Campelen era survey; indices since 1996 therefore tend to be closer, in relative terms, to the underlying estimates of biomass from the model.

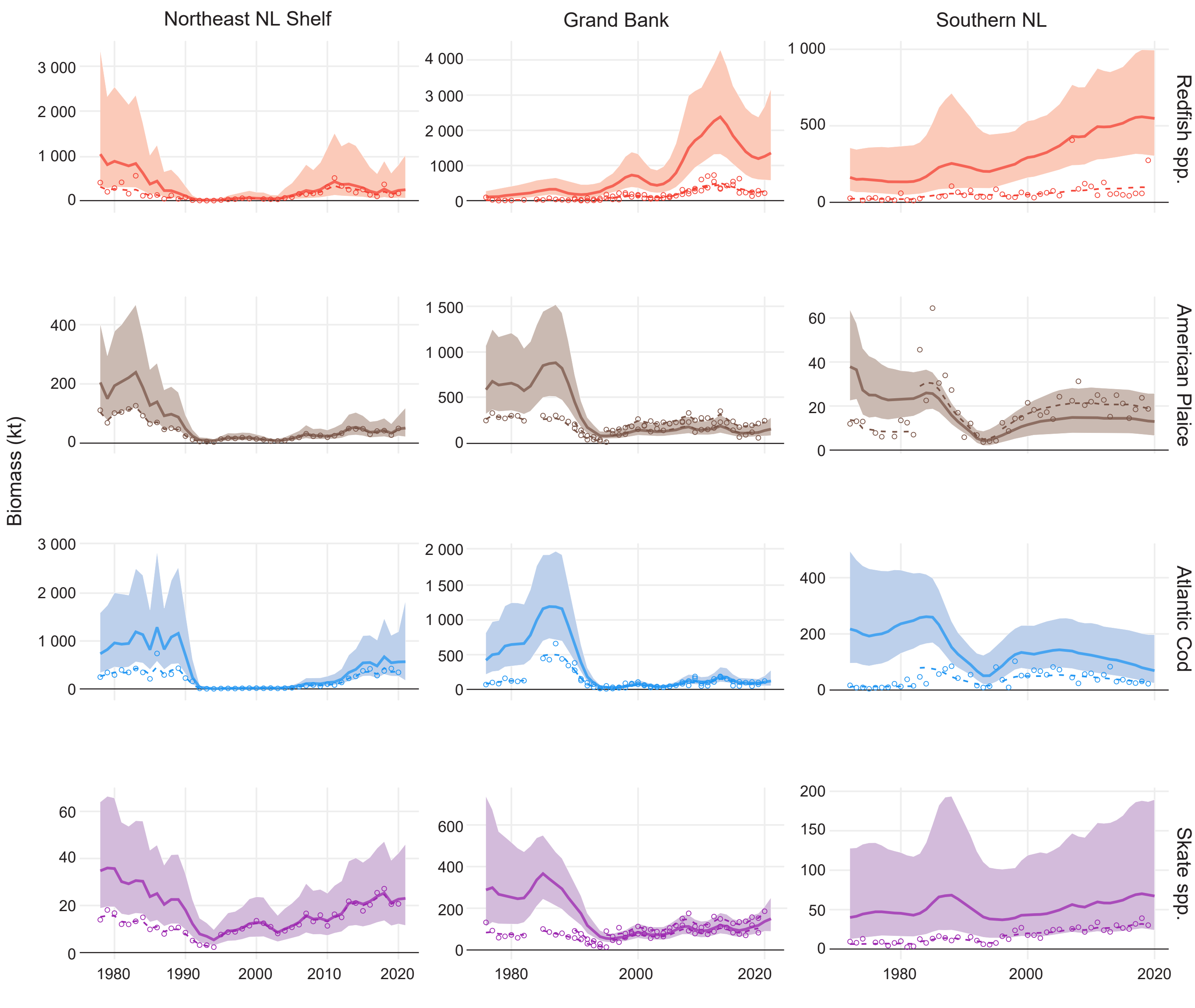


Fig. 3: Trends in survey indices (dots) along with predicted indices (dotted lines) and model estimates of biomass from the best fitting multispecies production model (solid lines). Uncertainty in the biomass estimates are represented by 95% confidence intervals (shaded region). Results from three ecosystem production units (Northeast NL Shelf, Grand Bank, and Southern NL) off the east coast of Canada are presented. Though data from seven species were used in each region, the species facet is limited to four for simplicity. Differences in biomass estimates from the indices stem from differing survey catchability estimates. Note differences in scale across facets.

Isolating residual changes in biomass not explained by reported fisheries landings or the production function (equation (4)) highlights deviations that can be either additions (positive residuals) or subtractions (negative residuals) to total biomass (Fig. 4). Substantial additions occurred throughout the 1980s, followed by sharp subtractions in the early 1990s across all three ecosystem production units. On the Northeast NL Shelf, biomass exceeded the estimated carrying capacity throughout much of the 1980s, and residual subtractions exceeding 500 kt per year precede the abrupt declines of the early 1990s. Most species have since recovered on the Northeast NL Shelf, with total biomass approaching carrying capacity while community composition has remained largely unchanged. On the Grand Bank, total biomass only briefly exceeded carrying capacity in the 1980s and, following declines in the early 1990s, subsequent increases were dominated by redfish spp. Off Southern NL, biomass remained below carrying capacity until the late 2010s, with smaller declines in the early 1990s and later increases largely driven by redfish spp.

Further inspection of the process errors reveals common patterns across all focal species across three ecosystem

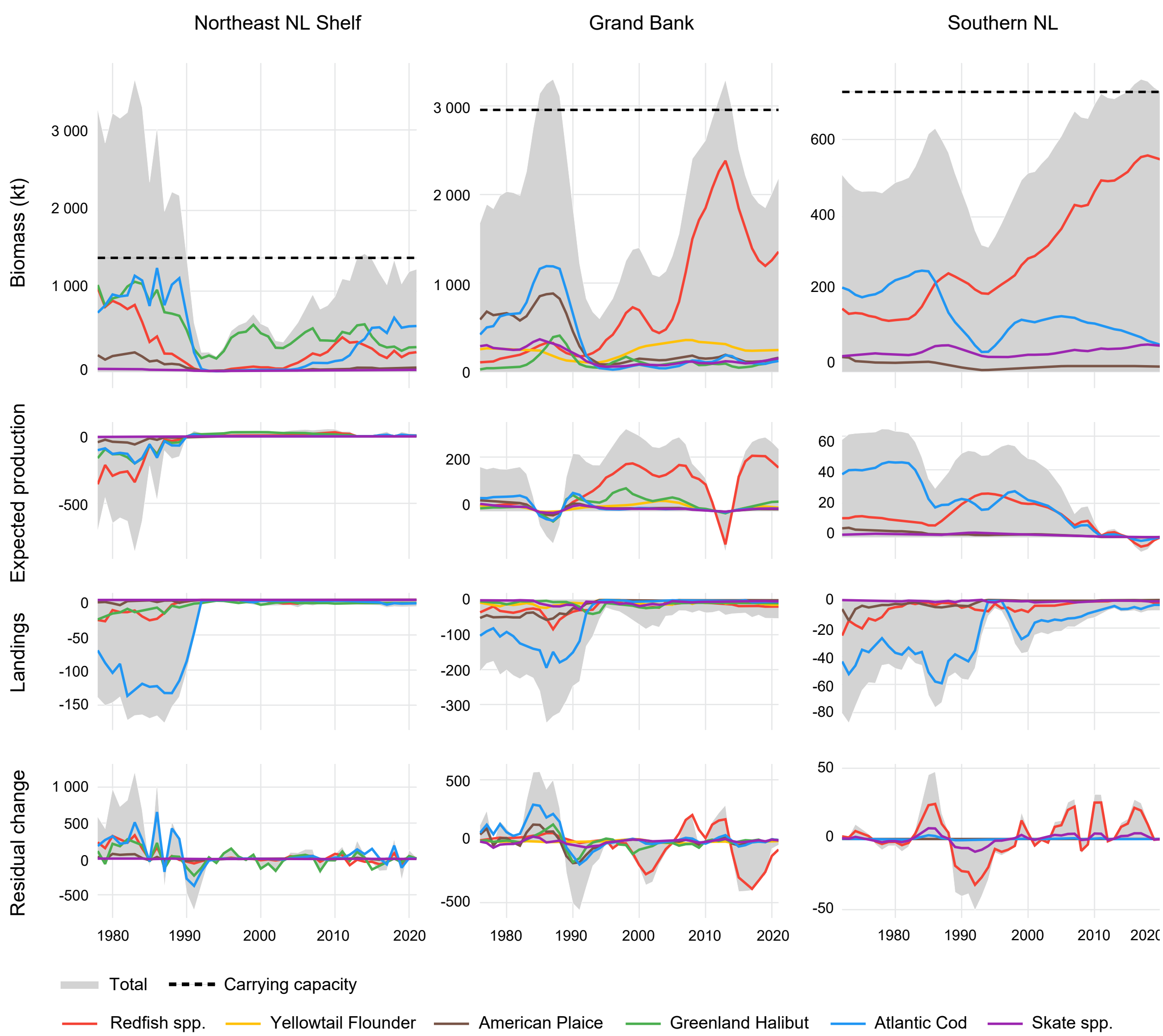


Fig. 4: Trends in biomass, expected production, reported landings, and residual change from the best fitting multispecies production model across three ecosystem production units (Northeast NL Shelf, Grand Bank, and Southern NL) off the east coast of Canada. Species-specific trends from a subset of species are shown along with totals including seven species. Expected production represents expected changes from intrinsic growth and density-dependence (*i.e.*, change from the production equation) and residual change represent process errors not explained by the production equation or reported landings. Note difference in scale across facets.

production units (Fig. 5). Like the exponentiated and unstandardized process errors ("residual change") shown in Fig. 4, the standardized process errors highlight substantive subtractions in the early 1990s, representing time-series lows for 19 out of 21 populations. The standardized values also reveal parallel and periodic increases and decreases within each region. The species-to-species correlations in the process errors estimated by the "just correlation" model indicate that 84% (53 of 63) of pairs were positively correlated. Also note that the "shared correlation" model estimates of a common species-to-species correlation parameter were 0.79 (95% CI: 0.70, 0.86), 0.68 (95% CI: 0.58, 0.76), and 0.81 (95% CI: 0.66, 0.90) for the Northeast NL Shelf, Grand Bank, and Southern NL ecosystem production units, respectively. This model received similar cross-validation scores as the "just correlation" model which, taken together, further supports the inference that the process errors are primarily positively correlated across species within each production unit.

Discussion

Rather than assuming that populations are primarily regulated by species-specific carrying capacities, our multispecies production model assumes that both intra and interspecific competition stunts growth as total biomass approaches the environment's maximal load. This assumption is conceptually similar to aggregate production models (Bundy *et al.*, 2012; Fogarty *et al.*, 2012; Mueter and Megrey, 2006) as it is rooted in the idea that total production, and consequently system-level MSY, is limited by the amount of resources available in a given ecosystem. In contrast to aggregate production models, we also attempt to capture the dynamics of species within a community. Fisheries landings, competitive interactions, predation, and prey availability all affect species-level production (Lotka, 1925; Schaefer, 1954; Volterra, 1926). While our model explicitly accounts for landings, species interactions are implicitly accounted for by estimating species-to-species correlations (*sensu* Albertsen *et al.*, 2018; see Gamble and Link, 2009 for a more explicit approach). Finally, by utilizing a state-space framework akin to single-species state-space production models (*e.g.*, Millar and Meyer, 2000; Winker *et al.*, 2018), we attempt to differentiate population processes from noise and bias from surveys of fish populations. The overall structure of the model allows species-specific dynamics to be captured while avoiding the assumption that the dynamics of each species is isolated and independent from other species sharing the same ecosystem production unit and potentially competing for the same resources.

Our case study focuses on the population dynamics of commercially important demersal fish stocks off the east coast of Canada. Stocks in the area collapsed in the early 1990s (Lear, 1998), and the relative contribution of fishing and environmental impacts has been highly

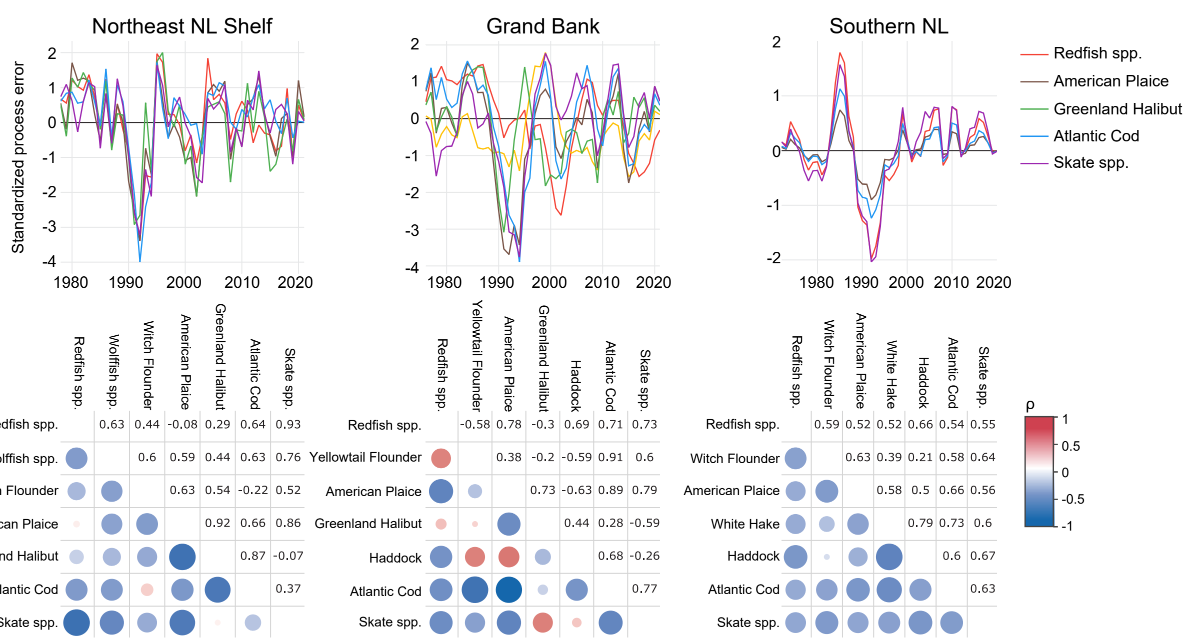


Fig. 5: Trends (upper facet) and species-to-species correlations (lower facet) in standardized process errors from the best fitting multispecies production model applied to seven species within three ecosystem production units (Northeast NL Shelf, Grand Bank, and Southern NL) off the east coast of Canada. Process errors represent changes not explained by the production equation or reported landings. Points in the correlation plots are coloured and scaled by the level of species-to-species correlation, ρ.

debated (Pedersen *et al.*, 2017). We attempt to disentangle the impacts of fishing from environmental effects using our multispecies production model and, in doing so, we provide empirical evidence that environmental factors played a non-negligible role in the changes observed in the region. First, we found general support for models with a system-level carrying capacity, consistent with the expectation that species within the same ecosystem production unit are constrained by a finite amount of available energy (Pepin *et al.*, 2014). Second, we found evidence for synchronous changes in the demersal fish community, which implies that a common bottom-up driver is impacting the dynamics of these species (see also Bundy *et al.*, 2012). This is supported by species-specific studies on capelin (*Mallotus villosus*) and Atlantic cod in the region which highlight the influence of bottom-up drivers (*e.g.*, Buren *et al.*, 2014b, 2014a; Koen-Alonso *et al.*, 2021; Regular *et al.*, 2022). Taken together, evidence is mounting that fishing was not the sole cause of the collapses observed in the early 1990s.

Our inference that environmental factors were a key driver of stock collapses was unexpected given the compelling narrative that fishing activity was the primary driver (*e.g.*, Gomes *et al.*, 1995; Hutchings, 1996). Since our model utilizes *reported* fisheries landings, a portion of these losses may be attributed to illegal fishing activity. However, it seems unlikely that the industry had the capacity to extract the amount needed to match the estimated losses. For instance, annual catches in the late 1980s across the Northeast NL Shelf and the Grand Bank totaled ~450 kt while residual losses estimated by the model in the early 1990s was ~1 000 kt. The fishing industry would have had to covertly double its efforts to explain the declines. It follows that the decline must at least in part, if not primarily, be due to an unknown environmental driver. This contention is not new (Atkinson, 1994; see, for example, Morgan *et al.*, 2002; Pedersen *et al.*, 2017), however, it remains contentious and perplexing as we lack specific causal explanations. While increasingly cold conditions through the 1980s and early 1990s undoubtedly affected the distribution of multiple species (Montevecchi and Myers, 1997; Robertson *et al.*, 2021; Rose *et al.*, 2000), it is not yet clear whether shifting temperatures was the primary driver of the collapse and, if it was, the causal pathway has yet to be determined.

Regardless of the environmental driver behind the 1990s collapse, it is possible that increasingly industrialized and intense fishing activity through the 1960s and 1970s reduced population diversity and, consequently, hampered the ability of the species within the community to buffer subsequent environmental changes (*sensu* the portfolio effect, Schindler *et al.*, 2010). Yet, a recent study found no evidence of genetic diversity loss in heavily exploited species like Atlantic cod (Pinsky *et al.*, 2021). Another hypothesis is that fishing activity bounded the safe operating space of the system, triggering an alternate stable state (Scheffer *et al.*, 2015). While not a perfect test of chaotic dynamics, we did assess the possibility of a systematic shift in system-level carrying capacities and found little support for this hypothesis.

Although we found little support for a structural shift, clear changes in community structure were evident. These shifts may have emerged from the combined effects of ocean climate fluctuations (Cyr *et al.*, 2025), interspecific competition, and shifting energy pathways. It is well known that the dominant forage species in the area shifted from capelin to shrimp (Dawe *et al.*, 2012) and this change was detrimental for cod (Link and Sherwood, 2019; Mullowney and Rose, 2014; Regular *et al.*, 2022) and perhaps other piscivorous species that rely on capelin. Shrimp are an important prey item for redfish species (Brown-Vuillemin *et al.*, 2022), so it is possible that the increasing shrimp population helped support concurrent recruitment pulses of redfish. We admit that this conjecture is speculative and acknowledge that the scale and dominance of redfish appears unrealistic; however, we add it as a simple example of how bottom-up forces may be driving the observed changes in the community. The reality is obviously more complex and the observed restructuring of the communities may be akin to the "paradox of plankton" where the continuous interaction of ecological and environmental factors give rise to "oscillations and chaos, with a continuous wax and wane of species within the community" (Scheffer *et al.*, 2003). In any case, our results suggest that the observed productivity changes in these ecosystems may be better explained by underlying environmental drivers than by a sudden structural shift to an alternate stable state.

Like all models, our multispecies production model is an imperfect abstraction of nature and while it may be useful in some contexts, it is important to consider its limitations when interpreting results. First, it is important to remember that there may be a spatial mismatch in the structure and function of the populations included in this study as some stock boundaries differ from the regions used in this study. For instance, Atlantic cod in NAFO divisions 2J3KL are considered a separate stock from cod in divisions 3NO (Templeman, 1962) and here we split 2J3K (Northeast NL Shelf) and 3LNO (Grand Bank) into distinct regions. Assuming that our results are comparable to previous results, it is peculiar that they indicate that total biomass in the Northeast NL Shelf production unit was above the carrying capacity of that region through the 1980s. This finding contradicts historic records that suggest populations such as Atlantic cod in 2J3KL were at substantially higher levels in the 1970s and earlier (Rose, 2004; Schijns *et al.*, 2021), which implies that the carrying capacity should be higher than estimated by the model presented here. Still, it is possible that the 1970s represents a period of unusually high productivity, where the system may have exceeded the carrying capacity (see also Cyr *et al.*, 2025). In our model, carrying capacity should be viewed as a long-term average, with environmental variability creating transient conditions that can raise or lower realized productivity.

Results from the Grand Bank and Southern NL also indicate that the demersal fish community is currently dominated by redfish and, consequently, the system's biomass appears to be approaching its carrying capacity. Though redfish are currently rebounding in parts of eastern Canada (Cadigan *et al.*, 2022), the implication that they dominate the demersal community seems unrealistic. This may be an artifact of low estimates of survey catchability or the model's inability to properly account for year effects. Observation errors are assumed to be lognormally distributed; however, extreme catch events or black swan events in space can introduce 'year effects' that may be better captured by a distribution with heavier tails, such as the t-distribution (Anderson and Ward, 2019). It is also possible that treating all species' biomass as equivalent in limiting growth has inflated the apparent role of redfish. This highlights the need to better evaluate how species differ in their contributions to density-dependence.

Despite these limitations, the approach holds practical value because it relies on inputs that are routinely collected in many regions (fishery-independent surveys and landings), making it broadly applicable in data-limited contexts. In turn, the multispecies production framework provides management-relevant outputs for ecosystem-based fisheries management (EBFM): it estimates community-level constraints (shared carrying capacity) and cross-species coherence, which can be used to design reference points and harvest control rules that recognize system-level limits and trade-offs among species (*sensu* Moffitt *et al.*, 2016; Mueter and Megrey, 2006). This type of application could complement the ecosystem reference point-based framework currently implemented in NAFO to inform on the risk of ecosystem overfishing (Koen-Alonso *et al.*, 2022; NAFO, 2022a, 2022b, 2022c). When residual dynamics become more synchronous, managers can apply stronger precautionary buffers to account for weakened portfolio effects (Schindler *et al.*, 2010). The model can also support projections conditioned on community dynamics, useful for testing rebuilding trade-offs. Because it is lightweight relative to end-to-end ecosystem models (*e.g.*, Fulton *et al.*, 2011) yet consistent with key principles of EBFM (Pikitch *et al.*, 2004), this approach offers a tractable option to embed multispecies dynamics and environmental considerations into existing assessment and strategy-evaluation workflows.

Conclusion

Practitioners are becoming increasingly aware of the need to apply EBFM (Pikitch *et al.*, 2004); however, progress has been impeded by a series of myths (Patrick and Link, 2015). One myth is that "EBFM can only be implemented in regions with copious data, and the corollary, doing EBFM requires models that are too complicated" (Patrick and Link, 2015). Our results support the arguments of Patrick and Link (2015) that data requirements need not be prohibitive, models need not be overly complex, and perfect knowledge of every process is not required to make meaningful progress. Using standard survey and catch data, the multispecies production model presented here offers a tractable means of estimating community-level constraints and multispecies trends, as well as producing species-specific projections conditioned on recent community dynamics. As such, it provides a framework for developing reference points and testing harvest control rules that recognize trade-offs among species. Echoing earlier arguments (Pikitch *et al.*, 2004), EBFM can and should be advanced even where data are limited. With minimal inputs, this method may help translate ecosystem considerations into operational advice, offering pragmatic support for the implementation of EBFM.

Acknowledgements

We thank the many ships' crew and research staff involved in leading the surveys and collecting the data used in this study. These surveys were supported by Fisheries and Oceans Canada (DFO). An earlier draft version of the abstract, introduction, and discussion sections were written with the assistance of ChatGPT (March 14, 2023 version).

References

Albertsen, C. M., Nielsen, A., and Thygesen, U. H. 2018. Connecting single-stock assessment models through correlated survival. *ICES Journal of Marine Science*, **75:** 235–244. https://doi.org/10.1093/icesjms/fsx114

Anderson, S. C., and Ward, E. J. 2019. Black swans in space: modeling spatiotemporal processes with extremes. *Ecology*, **100**: e02403. https://doi.org/10.1002/ecy.2403

Atkinson, D. B. 1994. Some observations on the biomass and abundance of fish captured during stratified-random bottom trawl surveys in NAFO Divisions 2J and 3KL, autumn 1981–1991. *NAFO Sci. Coun. Stud.*, **21**: 1–12.

Brown-Vuillemin, S., Chabot, D., Nozères, C., Tremblay, R., Sirois, P., and Robert, D. 2022. Diet composition of redfish (*Sebastes* sp.) during periods of population collapse and massive resurgence in the Gulf of St. Lawrence. *Frontiers in Marine Science*, **9**. https://doi.org/10.3389/fmars.2022.963039

Bundy, A., Bohaboy, E. C., Hjermann, D. O., Mueter, F. J., Fu, C., and Link, J. S. 2012. Common patterns, common drivers: comparative analysis of aggregate surplus production across ecosystems. *Marine Ecology Progress Series*, **459**: 203–218. https://doi.org/10.3354/meps09787

Buren, A. D., Koen-Alonso, M., Pepin, P., Mowbray, F., Nakashima, B., Stenson, G., Ollerhead, N., and Montevecchi, W. A. 2014a. Bottom-up Regulation of Capelin, a Keystone Forage Species. *PLoS One*, **9**: e87589. https://doi.org/10.1371/journal.pone.0087589

Buren, A. D., Koen-Alonso, M., and Stenson, G. B. 2014b. The role of harp seals, fisheries and food availability in driving the dynamics of northern cod. *Marine Ecology Progress Series*, **511**: 265–284. https://doi.org/10.3354/meps10897

Cadigan, N. G. 2015. A state-space stock assessment model for northern cod, including under-reported catches and variable natural mortality rates. *Canadian Journal of Fisheries and Aquatic Sciences*, **73**: 296–308. https://doi.org/10.1139/cjfas-2015-0047

Cadigan, N. G., Duplisea, D. E., Senay, C., Parent, G. J., Winger, P. D., Linton, B., and Kristinsson, K. 2022. Northwest Atlantic redfish science priorities for managing an enigmatic species complex. *Canadian Journal of Fisheries and Aquatic Sciences*, **79**: 1572–1589. https://doi.org/10.1139/cjfas-2021-0266

Chadwick, E., Brodie, W., Colbourne, E., Clark, D., Gascon, D., and Hurlbut, T. 2007. History of annual multi-species trawl surveys on the Atlantic coast of Canada. *Atlantic Zonal Monitoring Program Bulletin*, **6**: 25–42.

Chapman, E. J., and Byron, C. J. 2018. The flexible application of carrying capacity in ecology. *Global Ecology and Conservation*, **13**: e00365. https://doi.org/10.1016/j.gecco.2017.e00365

Cyr, F., Adamack, A. T., Bélanger, D., Koen-Alonso, M., Mullowney, D., Murphy, H., Regular, P., and Pepin, P. 2025. Environmental control on the productivity of a heavily fished ecosystem. *Nature Communications*, **16**: 5277. https://doi.org/10.1038/s41467-025-60453-6

Dawe, E., Koen-Alonso, M., Chabot, D., Stansbury, D., and Mullowney, D. 2012. Trophic interactions between key predatory fishes and crustaceans: comparison of two Northwest Atlantic systems during a period of ecosystem change. *Marine Ecology Progress Series*, **469**: 233–248. https://doi.org/10.3354/meps10136

Del Monte-Luna, P., Brook, B. W., Zetina-Rejón, M. J., and Cruz-Escalona, V. H. 2004. The carrying capacity of ecosystems. *Global Ecology and Biogeography*, **13**: 485–495. https://doi.org/10.1111/j.1466-822X.2004.00131.x

Fogarty, M., Overholtz, W., and Link, J. 2012. Aggregate surplus production models for demersal fishery resources of the Gulf of Maine. *Marine Ecology Progress Series*, **459**: 247–258. https://doi.org/10.3354/meps09789

Froese, R., Demirel, N., Coro, G., Kleisner, K. M., and Winker, H., 2017. Estimating fisheries reference points from catch and resilience. *Fish and Fisheries*, **18**: 506–526. https://doi.org/10.1111/faf.12190

Fulton, E. A., Link, J. S., Kaplan, I. C., Savina-Rolland, M., Johnson, P., Ainsworth, C., Horne, P., Gorton, R., Gamble, R. J., Smith, A. D., and Smith, D. C. 2011. Lessons in modelling and management of marine ecosystems: the Atlantis experience. *Fish and Fisheries*, **12**: 171–188. https://doi.org/10.1111/j.1467-2979.2011.00412.x

Gamble, R. J., and Link, J. S. 2009. Analyzing the tradeoffs among ecological and fishing effects on an example fish community: A multispecies (fisheries) production model. *Ecological Modelling*, **220**: 2570–2582. https://doi.org/10.1016/j.ecolmodel.2009.06.022

Gomes, M. C., Haedrich, R. L., and Villagarcia, M. G. 1995. Spatial and temporal changes in the groundfish assemblages on the north-east Newfoundland/Labrador shelf, north-west Atlantic, 1978–1991. *Fisheries Oceanography*, **4**: 85–101. https://doi.org/10.1111/j.1365-2419.1995.tb00065.x

Hilborn, R., Walters, C. J., and Ludwig, D. 1995. Sustainable exploitation of renewable resources. *Annual Review of Ecology and Systematics*, **26**: 45–67. https://doi.org/10.1146/annurev.es.26.110195.000401

Hutchings, J. A. 2021. A Primer of Life Histories: Ecology, Evolution, and Application. Oxford University Press. https://doi.org/10.1093/oso/9780198839873.001.0001

Hutchings, J. A. 1996. Spatial and temporal variation in the density of northern cod and a review of hypotheses for the stock's collapse. *Canadian Journal of Fisheries and Aquatic Sciences*, **53**: 943–962. https://doi.org/10.1139/f96-097

Kell, L. T., Kimoto, A., and Kitakado, T. 2016. Evaluation of the prediction skill of stock assessment using hindcasting. *Fisheries Research*, **183**: 119–127. https://doi.org/10.1016/j.fishres.2016.05.017

Koen-Alonso, M., Lindstrøm, U., and Cuff, A. 2021. Comparative Modeling of Cod-Capelin Dynamics in the Newfoundland-Labrador Shelves and Barents Sea Ecosystems. *Frontiers in Marine Science*, **8**: 579946. https://doi.org/10.3389/fmars.2021.579946

Koen-Alonso, M., Pepin, P., Fogarty, M., and Gamble, R. 2022. Review and Assessment of the Ecosystem Production Potential (EPP) model structure, sensitivity, and its use for fisheries advice in NAFO. *NAFO SCR Document*, 22/002: 1–52.

Kristensen, K., Nielsen, A., Berg, C., Skaug, H., and Bell, B. 2016. TMB: Automatic Differentiation and Laplace Approximation. *Journal of Statistical Software*, **70**: 1–21. https://doi.org/10.18637/jss.v070.i05

Latour, R. J., Brush, M. J., and Bonzek, C. F. 2003. Toward Ecosystem-Based Fisheries Management: Strategies for Multispecies Modeling and Associated Data Requirements. *Fisheries*, **28**: 10–22. https://doi.org/10.1577/1548-8446(2003)28[10:TEFM]2.0.CO;2

Lear, W. H., 1998. History of Fisheries in the Northwest Atlantic: The 500-year Perspective. *Journal of Northwest Atlantic Fishery Science*, **23**. https://doi.org/10.2960/J.v23.a4

Licandeo, R., Duplisea, D. E., Senay, C., Marentette, J. R., and McAllister, M. K. 2020. Management strategies for spasmodic stocks: A Canadian Atlantic redfish fishery case study. *Canadian Journal of Fisheries and Aquatic Sciences*, **77**: 684–702. https://doi.org/10.1139/cjfas-2019-0210

Link, J., and Sherwood, G. 2019. Feeding, Growth, and Trophic Ecology. *In*: Rose, G. A. (Ed.), Atlantic Cod: A Bio-Ecology. John Wiley & Sons, pp. 219–286. https://doi.org/10.1002/9781119460701.ch6

Lotka, A. J. 1925. Elements of physical biology. Williams and Wilkins.

Millar, R. B., and Meyer, R. 2000. Non-Linear State Space Modelling of Fisheries Biomass Dynamics by Using Metropolis-Hastings within-Gibbs Sampling. *Journal of the Royal Statistical Society: Series C (Applied Statistics)*, **49**: 327–342. https://doi.org/10.1111/1467-9876.00195

Moffitt, E. A., Punt, A. E., Holsman, K., Aydin, K. Y., Ianelli, J. N., and Ortiz, I. 2016. Moving towards ecosystem-based fisheries management: Options for parameterizing multi-species biological reference points. *Deep Sea Research Part II: Topical Studies in Oceanography*, **134**: 350–359. https://doi.org/10.1016/j.dsr2.2015.08.002

Montevecchi, W., and Myers, R., 1997. Centurial and decadal oceanographic influences on changes in northern gannet populations and diets in the north-west Atlantic: implications for climate change. *ICES Journal of Marine Science*, **54**: 608–614. https://doi.org/10.1006/jmsc.1997.0265

Morgan, M. J., Brodie, W., and Kulka, D. 2002. Was over-exploitation the cause of the decline of the American plaice stock off Labrador and northeast Newfoundland? *Fisheries Research*, **57**: 39–49. https://doi.org/10.1016/S0165-7836(01)00331-9

Mueter, F. J., and Megrey, B. A. 2006. Using multi-species surplus production models to estimate ecosystem-level maximum sustainable yields. *Fisheries Research*, **81**: 189–201. https://doi.org/10.1016/j.fishres.2006.07.010

Mullowney, D. R., and Rose, G. A. 2014. Is recovery of northern cod limited by poor feeding? The capelin hypothesis revisited. *ICES Journal of Marine Science*, **71**: 784–793. https://doi.org/10.1093/icesjms/fst188

NAFO, 2022a. Report of the NAFO Commission and its subsidiary bodies (STACTIC and STACFAD), 44th annual meeting of NAFO, 19–23 September 2022, Porto, Portugal. *NAFO COM Document*, 22/27: 168 p.

NAFO, 2022b. Report of the NAFO Joint Commission–Scientific Council working group on ecosystem approach framework to fisheries management (WG-EAFFM) meeting, 11–12 August 2022. *NAFO COM-SC Document*, 22–02: 1–22.

NAFO, 2022c. Report of the Scientific Council meeting, 03–16 June 2022. *NAFO SCS Document*, 22/18: 241 p.

NAFO, 2019. Report of the Scientific Council, 31 May – 13 June 2019, Halifax, Canada. *NAFO SCS Doc*, 19/20.

Patrick, W. S., and Link, J. S. 2015. Myths that Continue to Impede Progress in Ecosystem-Based Fisheries Management. *Fisheries*, **40**: 155–160. https://doi.org/10.1080/03632415.2015.1024308

Pauly, D., and Froese, R. 2021. MSY needs no epitaph—but it was abused. *ICES Journal of Marine Science*, **78**: 2204–2210. https://doi.org/10.1093/icesjms/fsaa224

Pedersen, E. J., Thompson, P. L., Ball, R. A., Fortin, M.-J., Gouhier, T. C., Link, H., Moritz, C., Nenzen, H., Stanley, R. R., Taranu, Z.E., Gonzalez, A. Guichard, F., and Pepin, P. 2017. Signatures of the collapse and incipient recovery of an overexploited marine ecosystem. *Royal Society Open Science*, **4**: 170215. https://doi.org/10.1098/rsos.170215

Pepin, P., Higdon, J., Koen-Alonso, M., Fogarty, M., and Ollerhead, N. 2014. Application of ecoregion analysis to the identification of Ecosystem Production Units (EPUs) in the NAFO Convention Area. *NAFO SCR Document*, 14/069, 1–13.

Pikitch, E. K., Santora, C., Babcock, E. A., Bakun, A., Bonfil, R., Conover, D. O., Dayton, P., Doukakis, P., Fluharty, D., Heneman, B., Houde, E. D., Link, J., Livingston, P. A., Mangel, M., McAllister, M. K. Pope, J., and Sainsbury, K. J. 2004. Ecosystem-based Fishery Management. *Science*, **305(5682)**. https://doi.org/10.1126/science.1098222

Pinsky, M. L., Eikeset, A. M., Helmerson, C., Bradbury, I. R., Bentzen, P., Morris, C., Gondek-Wyrozemska, A. T., Baalsrud, H. T., Brieuc, M. S. O., Kjesbu, O. S., Godiksen, J. A., Barth, J. M. I., Matschiner, M. Stenseth, N. C., Jakobsen, K. S., Jentoft, S., and Star, B. 2021. Genomic stability through time despite decades of exploitation in cod on both sides of the Atlantic. *Proceedings of the National Academy of Sciences*, **118**: e2025453118. https://doi.org/10.1073/pnas.2025453118

R Core Team. 2021. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Regular, P. M., Buren, A. D., Dwyer, K. S., Cadigan, N. G., Gregory, R. S., Koen-Alonso, M., Rideout, R. M., Robertson, G. J., Robertson, M. D., Stenson, G. B., Wheeland, L. J., and Zhang, F. 2022. Indexing starvation mortality to assess its role in the population regulation of Northern cod. *Fisheries Research*, **247**: 106180. https://doi.org/https://doi.org/10.1016/j.fishres.2021.106180

Robertson, M., Gao, J., Regular, P., Morgan, M., and Zhang, F. 2021. Lagged recovery of fish spatial distributions following a cold-water perturbation. *Scientific Reports*, **11**: 9513. https://doi.org/10.1038/s41598-021-89066-x

Rose, G. 2004. Reconciling overfishing and climate change with stock dynamics of Atlantic cod (*Gadus morhua*) over 500 years. *Canadian Journal of Fisheries and Aquatic Sciences*, **61**: 1553–1557. https://doi.org/10.1139/f04-173

Rose, G., DeYoung, B., Kulka, D., Goddard, S., and Fletcher, G. 2000. Distribution shifts and overfishing the northern cod (*Gadus morhua*): A view from the ocean. *Canadian Journal of Fisheries and Aquatic Sciences*, **57**: 644–663. https://doi.org/10.1139/f00-004

Schaefer, M. B. 1954. Some aspects of the dynamics of populations important to the management of the commercial marine fisheries. *Inter-American Tropical Tuna Commission Bulletin*, **1**: 23–56.

Scheffer, M., Barrett, S., Carpenter, S., Folke, C., Green, A. J., Holmgren, M., Hughes, T., Kosten, S., Van de Leemput, I., Nepstad, D., van Nes, E. H., Peeters, E. T. H. M., and Walker, B. 2015. Creating a safe operating space for iconic ecosystems: Manage local stressors to promote resilience to global change. *Science*, **347**: 1317–1319. https://doi.org/10.1126/science.aaa3769

Scheffer, M., Rinaldi, S., Huisman, J., and Weissing, F. J. 2003. Why plankton communities have no equilibrium: solutions to the paradox. *Hydrobiologia*, **491**: 9–18. https://doi.org/10.1023/A:1024404804748

Schijns, R., Froese, R., Hutchings, J. A., and Pauly, D. 2021. Five centuries of cod catches in Eastern Canada. *ICES Journal of Marine Science*, **78**: 2675–2683. https://doi.org/10.1093/icesjms/fsab153

Schindler, D. E., Hilborn, R., Chasco, B., Boatright, C. P., Quinn, T. P., Rogers, L. A., and Webster, M. S. 2010. Population diversity and the portfolio effect in an exploited species. *Nature*, **465**: 609–612. https://doi.org/10.1038/nature09060

Smith, S., and Somerton, G. 1981. STRAP: A User-Oriented Computer Analysis System for Groundfish Research Trawl

Survey Data. *Canadian Technical Report of Fisheries and Aquatic Sciences*, No. 1030.

Templeman, W. 1962. Divisions of cod stocks in the northwest Atlantic. *ICNAF Redbook*, **3**: 79–123.

Thorson, J. T. 2020. Predicting recruitment density dependence and intrinsic growth rate for all fishes worldwide using a data-integrated life-history model. *Fish and Fisheries*, **21**: 237–251. https://doi.org/10.1111/faf.12427

Volterra, V. 1926. Fluctuations in the Abundance of a Species considered Mathematically. *Nature*, **118**: 558–560. https://doi.org/10.1038/118558a0

Walsh, S. J. 1992. Size-Dependent Selection at the Footgear of a Groundfish Survey Trawl. *North American Journal of Fisheries Management*, **12**: 625–633. https://doi.org/10.1577/1548-8675(1992)012%3C0625:SDSATF%3E2.3.CO;2

Winker, H., Carvalho, F., and Kapur, M. 2018. JABBA: Just Another Bayesian Biomass Assessment. *Fisheries Research*, **204**: 275–288. https://doi.org/10.1016/j.fishres.2018.03.010

J. Northw. Atl. Fish. Sci., Vol. 57, Special Issue: 17–25
Conference article

Publication (Upload) date: 11 Sep. 2026

Unseen but Connected: Exploring How Connectivity Informs the Ecosystem Approach to Fisheries Management in the Northwest Atlantic Fisheries Organization

Ellen Kenchington
Fisheries and Oceans Canada, Bedford Institute of Oceanography,
Dartmouth, NS Canada B2Y 4A2
Ellen.Kenchington@dfo-mpo.gc.ca

Kenchington, E. 2026. Unseen but Connected: Exploring how connectivity informs the Ecosystem Approach to Fisheries Management in the Northwest Atlantic Fisheries Organization. *J. Northw. Atl. Fish. Sci.*, **57(1)**: 17–25. https://doi.org/10.2960/J.v57.m759

Abstract

Connectivity, a key property of marine ecosystems operating over various spatial scales, relies on movements of organisms, nutrients and energy. Those can be active, involving directed migration, or passive, the latter relying on transport by physical mechanisms that transport organisms, including gametes and larvae. Dispersal drives population dynamics and community structure, hence is an essential component to consider in an Ecosystem Approach to Fisheries Management (EAFM). In the Northwest Atlantic Fisheries Organization (NAFO), connectivity has been considered in a number of different contexts and applications. The distribution ranges of major marine fish species, a product of their dispersal, amongst other aspects, helped to inform the establishment of Bioregions, Ecosystem Production Units, and Ecoregions – nested spatial scales identified as relevant to the development of ecosystem summaries and management plans. For sessile and sedentary benthic species, such as the corals and sponges identified as Vulnerable Marine Ecosystem (VME) indicators, connectivity within and among high-density habitats is key to habitat formation and continuation. In such species, connectivity is governed by larval transport, predominantly by bottom currents. Recently, NAFO has used 3-D Lagrangian particle tracking models to identify connectivity networks of both the closed areas and identified VME habitats, in support of an EAFM. Here, an overview of how NAFO has incorporated information on connectivity into its decision-making processes is provided.

Key words: connectivity, vulnerable marine ecosystems, NAFO, EAFM

Introduction

Species' distributions underpin an Ecosystem Approach to Fisheries Management (EAFM) and spatial connectivity, defined as the movement of adults, gametes or larvae across space (Hanski, 1998; Tischendorf and Fahrig, 2000), is an important property of marine ecosystems that influences species' distributions (Wang *et al.*, 2021), as well as community composition (Costello and Chaudhary, 2017; Monteiro *et al.*, 2017), nutrient transport (Palter *et al.*, 2010; Fripiat *et al.*, 2021), and ultimately the productivity (McClain *et al.*, 2004; Doddridge and Marshall, 2018), dynamics (Watson *et al.*, 2012), resistance/resilience (Carr *et al.*, 2017) and restoration (McRae *et al.*, 2012) of ecosystems. It does so through exchange and subsidies of organisms, nutrients, and energy within and across population boundaries (Spanowicz and Jaeger, 2019), while driving population dynamics and community structure (Lundberg and Moberg, 2003; Pineda *et al.*, 2007), and thus is an essential component to consider in an EAFM (Shanks *et al.*, 2003).

Mediated through both active and passive biological and environmental processes, connectivity is influenced by (among others) currents, bathymetric features, internal waves and tides, boundary layers and the thermo-haloclines between water masses, which can affect vertical movement of organisms (Crooks and Sanjayan, 2006; Pineda *et al.*, 2007). Those physical factors may not entirely constrain movements of active, nektonic animals but does influence their distributions (Dahms and Killen, 2023), while the dispersal trajectories of those sessile and sedentary species which rely on larval transport can be primarily determined by physical processes (Cowen and Sponaugle, 2009).

The importance of connectivity in the maintenance of healthy and productive marine ecosystems has been recognized in international policy, both under the auspices of protecting biodiversity and for sustainable use of the oceans. The Convention on Biological Diversity (CBD) introduced connectivity as a property of marine protected area (MPA) network design under Aichi Biodiversity Target 11 (CBD COP 10 Decision X/2). This property has been retained in the 2022 Kunming-Montreal Global Biodiversity Framework (GBF) adopted by CBD COP 15 under Target 3 (CBD Decision 15/4). The CBD guidance notes for Target 3 provide the following definition:

> "Well-connected – In order for protected areas and OECMs [Other Effective Area-Based Conservation Measures] to be effective, they should be connected through corridors as well as integrated into wider landscapes, seascapes and the ocean. This is an essential element of creating effective systems or networks of protected and conserved areas that can meet sustained in situ conservation outcomes and cope with stresses and disturbances, including from the impacts of climate change."[1].

The GBF identifies the Protected Area Connectedness Index (PARC-Connectedness) and ProtConn (Protected Connected Index) as component indicators for Target 3. The PARC index measures the extent to which protected areas are functionally connected to one another and to other areas of intact natural ecosystems[2]. It was developed for terrestrial ecosystems but has analogues in the marine environment (Kenchington *et al.*, 2018). The ProtConn index measures the percentage of land covered by protected and connected lands (Saura *et al.*, 2018). It was developed for reporting on Aichi Target 11 but has been retained for the GBF. The Protected Area Isolation Index (PAI) which measures how connected each of the world's protected areas (PAs) are, focuses on the movement of terrestrial animals between habitats (Brennan *et al.*, 2022) and is considered a complimentary indicator to Target 3.

Connectivity has also been introduced into the United Nations Sustainable Fisheries resolutions, first appearing in 2022 in the General Assembly Resolution A/Res/77/118[3] in relation to both Vulnerable Marine Ecosystems (VMEs) (paragraph 212) and fish stocks (paragraph 216). With respect to VMEs, the resolutions call for regional fisheries management organizations, such as the Northwest Atlantic Fisheries Organization (NAFO):

> *"*...to identify and overcome barriers to the implementation of the relevant paragraphs of General Assembly resolutions 64/72, 66/68 and 71/123 such as data availability, especially with regard to baseline data and the spatial distribution and connectivity of vulnerable marine ecosystems…".

While connectivity in the deep-sea can be difficult to measure empirically, NAFO Scientific Council has responded to this call by developing biophysical models to elucidate the connectivity networks of VMEs and of the closed areas within its Regulatory Area. In this contribution, I provide an overview of how NAFO has incorporated information on connectivity into its decision-making process. Whenever relevant, I go beyond a recount of the facts and share my perspectives on the provision of scientific advice on this topic.

The Ecosystem Approach to Fisheries Management in NAFO and the Role of Connectivity

In NAFO, connectivity has been considered, directly or indirectly, in a number of different spatial contexts and applications (Table 1). The spatial structure of physical and biological features, including the distribution ranges of major fish stocks, helped to inform the establishment of three nested spatial scales, Bioregion, Ecosystem Production Unit (EPU), and Ecoregion, that were identified as relevant to the development of ecosystem summaries and management plans (Pepin *et al.*, 2014; NAFO, 2014). They serve as a framework supporting implementation of an EAFM (Koen-Alonso *et al.*, 2019). The NAFO Working Group on the Ecosystem Approach to Fisheries Management (WG-EAFM) (now the 'Working Group on Ecosystem Science and Assessment', WG-ESA) considered this issue at its first meeting in June of 2008, under its first two Terms of Reference:

> *ToR 1: To identify regional ecosystems in the NAFO Convention Area, and*
>
> *ToR 2: To make an inventory of current knowledge on the components of each regional ecosystem* (NAFO, 2008).

A spatially and temporally extensive set of observations of bathymetric, oceanographic and biotic variables was analyzed to identify regions and subregions of biophysical similarity/dissimilarity or Bioregions (NAFO, 2008; Zwanenburg *et al.*, 2010; Pepin *et al.*, 2010; Pepin *et al.*, 2014). Each Bioregion is composed of one or more EPUs. Those do not represent closed systems, but they generally correspond to the distributions of particular, major groundfish stocks, while having a coherent fish community structure internally (Koen-Alonso *et al.*, 2019). Within an EPU, geographical areas with consistent physical and biological characteristics are defined as Ecoregions. It is within this spatial scale that more precisely defined habitats (such as VME habitats) can be identified. Subsequently, EPUs and Ecoregions have been used by NAFO Scientific Council while generating ecosystem-science advice (NAFO, 2015b; Koen-Alonso *et al.*, 2019). They have been paralleled in Canada, the adjacent coastal state, using similar methods (DFO, 2009). In hindsight, it might have been better to apply the term Ecoregion to the larger spatial scale Bioregion, to be consistent with its use elsewhere, such as in the International Council for the Exploration of the Sea (ICES) where an ecoregion is a spatial unit used to synthesize evidence for ecosystem-based management (ICES, 2004). These regions share

[1] https://www.cbd.int/gbf/targets/3#:~:text=Well%2Dconnected%20%E2%80%93%20In%20order%20for,to%20occur%20within%20their%20boundaries Accessed 8/14/2025.
[2] https://geobon.org/ebvs/indicators/protected-area-representatives-connectedness-indices/ Accessed 10/12/2025.
[3] https://docs.un.org/en/A/RES/77/118 Accessed 8/14/2025.

Table 1. Chronological development of the incorporation of information on connectivity into the science advice for NAFO.

Year	Benchmarks for the Use of Connectivity-Related Data in NAFO	Reference
2008	Delineation of ecoregions at three nested scales	NAFO (2008)
2010	Indices of biomass, abundance and biomass/abundance (BA) ratio were used to describe the changes in the fish community in two functional sub-units of the Newfoundland and Labrador Shelves Bioregion.	NAFO (2010)
	Elaboration of the overall EAFM framework described as a three-tiered, hierarchical one. The first tier defines fishery production potential at the EPU level, taking into account environmental conditions and ecosystem state.	NAFO (2010)
2011	"Roadmap for the development of and ecosystem approach to fisheries (EAF) for NAFO" introduced. Subsequent reports focus on developing and implementing the "Roadmap to EAF" which includes identification of VMEs.	NAFO (2011)
2012	First mention of connectivity in relation to recovery of sponge grounds from bottom-contact fishing.	NAFO (2012)
2013	Connectivity first raised in the assessment of areas closures for the protection of sea pen Vulnerable Marine Ecosystems (VMEs), for example: "the lack of protection for the entire eastern part of their distribution is of concern for the long term sustainability of these VME given the lack of knowledge of recruitment processes and connectivity ", "the areas between 13 and 14 should be linked for sustaining connectivity in this system", "the system of sea pen VMEs on Flemish Cap".	NAFO (2013)
	WG-ESA notes that "the closed areas should be viewed as connected systems".	NAFO (2013)
2015	"Index of Risk of VME fragmentation", the proportion of discrete VME without protection, introduced for the assessment of Significant Adverse Impacts (SAI) of bottom-contact fishing (sensu FAO, 2009). This risk was incorporated into "Overall SAI risk scores" for sponge, sea pen and large gorgonian VME in the NAFO Regulatory Area (NRA).	NAFO (2015b)
	ToRs for WG-ESA updated and include: Spatial Considerations. ToR 2. In support of the Roadmap, develop research and summarize new findings on the spatial structure and organization of marine ecosystems, with emphasis on connectivity, exchanges and flows among ecosystem units in the NAFO Convention Area.	NAFO (2015b)
2018	Connectivity agreed to be a part of the re-assessment of VME closures in 2020: "Consideration of the connectivity of VMEs through links between propagule/larval transportation and VME distribution/location... should be included. This will highlight the importance of certain VME closed areas in supporting larval dispersal and recruitment between other VME closed areas of the same type…"	NAFO (2018)
	First assessment of connectivity among closed areas within the fishing footprint in the NRA.	Kenchington *et al.* (2018); NAFO (2018)
	Agent-based modeling of sea pens introduced for understanding the level of connectivity and dependence among the distinct aggregations that exist on the seascape.	NAFO (2018)
2019	"Projected Connectivity Among Closures" added to the assessment of SAI to be applied to the reassessment of bottom fisheries in 2021. Connectivity is defined as the "physical links between two or more areas; an area is considered to have redundancy when two or more other areas connect to it. These properties relate to the ability of populations to persist.".	NAFO (2019); Wang *et al.* (2019)
	Connectivity discussed as a part of the re-assessment of VME closures and included in the identification of High Priority Areas for Management Action.	NAFO (2019)
2020	VME Closure Connectivity Index developed based on enhanced model developments and connectivity characteristics for each of the areas closed to protect large gorgonian corals, sea pens and sponges in the NRA, including outputs from 3D forward- and backward-tracking biophysical models using yearly and seasonally averaged oceanographic models.	NAFO (2020); Wang *et al.* (2020)
	"Importance as a Larval Source for other Closed Areas" introduced to the review of the closed areas in addition to retention and redundancy.	NAFO (2020)
	Agent-based modeling of sea pens identified that, in the absence of fishing, recovery of an area could take place in 50 years. Also that, under current fishing scenarios, sea pen connectivity might be compromised, leading to longer recovery times. In the case of the NAFO closures, recovery time could exceed 100 years.	NAFO (2020)
	Proposed management actions prioritized based on connectivity. The lowest priority for management action is for 'Sink' areas that have 'Moderate' to 'Strong' Redundancy, on the basis that such areas likely receive larvae from other closed areas to retain their local populations. Other scenarios are discussed.	NAFO (2020)
	Isolation/Proximity Index as a measure of VME fragmentation introduced.	NAFO (2020)
	Work of WG-ESA on connectivity discussed in the context of Other Effective Area-Based Conservation Measures (OECMs).	NAFO (2020)
2021	Application of Isolation/Proximity Indices to Large-sized sponge VMEs	NAFO (2021a)
2022	Connectivity among VMEs evaluated using particle tracking models applied to the seven VME indicator taxa (Large-size sponges, Sea pens, Large and Small gorgonian corals, Black corals, Sea squirts and Erect bryozoans).	NAFO (2022a)
2024	Publication of simulations of VME habitat loss on connectivity networks for each of the VME indicator taxa.	Wang *et al.* (2024)
2025	When the six sponge areas in the NRA were submitted to the World Protected Area database as OECMs, they were considered to be ecologically connected based on connectivity analyses conducted in WG-ESA.	https://www.nafo.int/Fisheries/OECMs [Accessed 8/14/2025]

similar oceanographic conditions, habitats, and biological communities, as do the NAFO Bioregions. Further, Fisheries and Oceans Canada (DFO, 2016) uses the term 'Biological Facies', to refer to a fine-scale unit used to represent specific biological habitat types, such as a VME habitat, which would nest well within the EPU.

Genetic Population Structure

Genetic studies can reveal that wide-ranging species (*e.g.*, Atlantic cod (*Gadus morhua*)) are composed of a number of smaller, locally adapted populations. Without this knowledge, high fishing pressure might extirpate one population, reducing the overall genetic diversity and stability of the species, even if the overall harvest remains high. Genetic markers can be useful tools for understanding the stock structure of fish populations, revealing patterns of connectivity and differentiation that inform both delineation of EPUs and the management of fisheries more generally (Begg *et al.*, 1999). Gene flow, defined as the movement of genes from one population to another through the migration of individual organisms that subsequently reproduce in their new population, influences fish stock structure, with high gene flow leading to less genetic differentiation and potentially a single genetic stock, while restricted gene flow can lead to distinct stocks (Cano *et al.*, 2008; Hellberg 2009). Mating may occur in discrete areas (spawning grounds), sometimes associated with natal homing (*e.g.*, Atlantic cod: Bonanomi *et al.*, 2016) which can result in genetically distinct populations (*e.g.*, Ruzzante *et al.*, 2006). Genetic analyses have helped to determine stock structure in a number of species occurring in the NAFO area, including northern shrimp (*e.g.*, Jorde *et al.*, 2015), Atlantic cod (*e.g.*, Ruzzante *et al.*, 1999), Greenland halibut (*e.g.*, Estévez-Barcia *et al.*, 2025), redfish (*e.g.*, Roques *et al.*, 2002), and capelin (*e.g.*, Kenchington *et al.*, 2015).

There are few population genetic studies of VME indicator species in the NAFO Convention Area, and none within the fishing footprint of the NAFO Regulatory Area (NRA). This is in part due to limited opportunities to conduct appropriate sampling at depth, which ideally involves collection of numerous individuals using a remotely operated vehicle (ROV) from a number of putative populations over the full range of the species' distribution. Particle tracking models which identify connectivity networks (see below), as well as species distribution models which identify suitable habitat (*e.g.*, Murillo *et al.*, 2024; Murillo *et al.*, 2025), can help to identify appropriate sampling locations within large geographic settings. Nevertheless, population genetics of the deep-sea glass sponge, *Vazella pourtalesii*, a VME indicator taxon (NAFO, 2025) which occurs in the broader NAFO Convention Area and was sampled with a ROV, has revealed patterns of genetic diversity, structure, and connectivity (Patova *et al.*, 2025). Further, studies of the deep-sea coral genus *Paramuricea*, captured in the NAFO Convention Area with bottom trawls, gillnets and longlines, indicated distinct, diverse genetic structure across its range to the Gulf of Mexico, and cryptic species in waters off Newfoundland and Labrador (Radice *et al.*, 2016); the latter being crucial information for the assessment of connectivity in this genus.

Connectivity and Vulnerable Marine Ecosystems

As part of an EAFM, the protection of VMEs from significant adverse impacts (SAI) of bottom-contact fishing gear is required under the UN Sustainable Fisheries resolutions. In this context, VMEs are NAFO Ecoregions with physical and biological characteristics that render them especially vulnerable. The International Guidelines for the Management of Deep-sea Fisheries in the High Seas of the Food and Agriculture Organization of the United Nations (FAO, 2009) provide a suite of characteristics for the selection of VME indicator species which can serve to define and delineate such Ecoregions (NAFO, 2015a). NAFO Scientific Council has applied those Guidelines to data on over 500 trawl-caught benthic invertebrate taxa (Murillo *et al.*, 2011) and identified nine functional groups of VME indicators, all of which form habitats of mixed species composition, *viz.*: Large-size Sponges, Sea Pens, Large Gorgonian Corals, Small Gorgonian Corals, Black Corals, Erect Bryozoans, Sea Squirts, Sea Lilies (Crinoids) and Tube-dwelling Anemones (NAFO, 2025). In Ecoregions where these structure-forming VME indicators occur in large concentrations (NAFO, 2019; Kenchington *et al.*, 2025), ecological processes may be highly dependent on the dominant taxa (*e.g.*, Pham *et al.*, 2019; Murillo *et al.*, 2020a; Murillo *et al.*, 2020b; Stratmann *et al.*, 2024).

Once the VME indicators were identified, NAFO Scientific Council used a kernel density analysis and areal expansion technique to identify VME Ecoregions for each of seven functional groups of VME indicators for which data were available (Kenchington *et al.*, 2019; Kenchington *et al.*, 2025). Sea Lilies and Tube-dwelling Anemones were not evaluated.These VME Ecoregions were used to inform a series of spatial closures where bottom-contact fishing gears are prohibited (NAFO, 2025).

Connectivity issues among VME Ecoregions were first discussed by WG-EAFM at its 2012 meeting in the context of SAI on VMEs, where it was stated that connectivity amongst the sponge grounds will influence recovery dynamics (Table 1; NAFO, 2012). The following year, the Fisheries Commission requested science advice regarding sea pen closures on the Flemish Cap. WG-ESA described the sea pens as "a system of sea pen VME", and it was noted that "the lack of protection for the entire eastern part of their distribution [was] of concern for the long term sustainability of these VME given the lack of knowledge of recruitment processes and connectivity" (NAFO, 2013). By 2015, NAFO had incorporated aspects of habitat configuration (arrangement of the VMEs in space), as part of its assessment of SAI, in an "Index of Risk of VME fragmentation" defined as the "Proportion of discrete VME without protection" (NAFO, 2015b). This is the inverse of the ProtConn indicator under the GBF. Recognizing the importance of connectivity to the structure and functioning of marine ecosystems, WG-ESA proposed an update and revision of its long-term ToRs to incorporate connectivity, accordingly (Table 1):

> *ToR 1. Update on identification and mapping of sensitive species and habitats in the NAFO area. In support of the Roadmap develop research and summarize new findings on the spatial structure and organisation of marine ecosystems with an emphasis on connectivity, exchanges and flows among ecosystem units in the NAFO Convention Area* (NAFO, 2016).

This change to the WG-ESA ToRs stimulated primary research on connectivity (Table 1), and in 2018 work was presented to WG-ESA detailing an assessment of connectivity among closed areas within the fishing footprint of the NRA (Kenchington *et al.*, 2018; NAFO, 2018). An agent-based modelling approach was also explored as a means to study the impacts of commercial fishing on sea pens (NAFO, 2018).

A metric of habitat configuration that incorporates habitat area and nearest neighbour distances (PX; Gustafson and Parker, 1994) was applied to the distributions of each VME previously identified by kernel density analyses, and to the configuration of the spatial closures. Lagrangian particle tracking models were used to estimate connection distances among VMEs and among closed areas. Such modeling approaches being the most practical means of assessing connectivity of benthic invertebrate VME indicators in the deep sea, where the remoteness of the region makes other approaches, such as population genetics, impractical (see above). Initially the models were 2-D, allowing only horizontal movement (NAFO, 2018; Kenchington *et al.*, 2019), and to address this deficiency, model larvae were released at different vertical positions within the water column to track their dispersal. However, by 2021, more realistic connections among the closed areas and among the VMEs were evaluated based on connectivity modeling using 3-D Lagrangian particle tracking models which included vertical movement and were run in both forward and hindcast directions (Wang *et al.*, 2021, 2024; NAFO, 2021a). These models allowed the model larvae to passively move through the water column. Although different modeling scenarios can be run to compensate for a lack of knowledge of spawning times, larval duration and behaviour of VME indicator taxa, further information on the reproductive biology of these taxa would enable more precise models to be performed (see Kenchington *et al.* (2018) for knowledge gaps and compensatory modeling). The particle tracking trajectories resulting from these modeling scenarios identify the connectivity networks among VME habitats, including source-sink relationships, and complement species distribution models to quantify probabilities of recruitment to areas of predicted presence (*e.g.*, Wang *et al.*, 2022).

Based on this body of work, different ways of capturing the information on the connectivity network design were presented in the form of connectivity indices (NAFO, 2020). Connectivity and habitat configuration were subsequently incorporated into the assessment and recommendations for closed area protection of the VMEs (NAFO, 2021a). Meanwhile, WG-ESA defined connectivity and connectivity networks in the context of their work on VMEs as:

> "physical links between two or more areas; an area is considered to have redundancy when two or more other areas connect to it. These properties relate to the ability of populations to persist" (NAFO, 2020).

Most recently, simulated removal of single VME habitats was modeled. Very considerable differences were found amongst those areas in their effects on network configuration, as measured by the change in PX resulting from their deletions (Gustafson and Parker, 1994, NAFO, 2022a). PX is an index of habitat configuration that incorporates habitat area and nearest neighbour distances, and is similar to the GBF indicator PARC, which measures the extent to which protected areas are functionally connected to one another. Removal of many VMEs, 28 of the 84, had little effect on the PX (declines of < 0.05%) but, in each of the seven VME indicator functional groups, there was at least one VME habitat that, when removed, reduced the index by more than 45% and, in some cases, by more than 85% (NAFO, 2022a; Wang *et al.*, 2024). While PX cannot capture every important aspect of network configuration, it is clear that some VMEs are much more important to achievement of overall conservation goals than are others.

In preparing for the 2027 NAFO review of the placement and effectiveness of the areas closed to bottom fishing to protect VMEs, WG-ESA agreed to consider the work done on connectivity since the last review and to consider the best way to incorporate those results into the assessment of SAI. It was noted that there are many VMEs that are not protected by area closures. For those VME connectivity networks that are only partially protected, the unprotected VMEs could be important sources of recruitment inside the closed areas, and loss or diminishment of such unprotected VMEs could undermine NAFO efforts to effectively protect VMEs through implementation of spatial closures, and hence the implementation of an EAFM (NAFO, 2024).

In going forward, NAFO could frame its connectivity indices using the terminology of the GBF Target 3 indicators (*i.e.*, PARC-Connectedness and ProtConn) when applicable, so as to parlay its work into broader global assessments.

Uptake of Science Advice on Connectivity of VMEs by Managers

Despite the importance of connectivity for the protection of VMEs being first raised by WG-EAFM in 2012 (Table 1), it was over a decade later that clear evidence of consideration of connectivity became apparent in management actions (NAFO, 2022b). The research undertaken by WG-ESA in 2020 emphasized the importance of connectivity networks for the protection of VMEs with an emphasis on sea pen connectivity (NAFO, 2020). Subsequently, in 2021, the NAFO 'Working Group on the Ecosystem Approach Framework to Fisheries Management' (WG-EAFFM) specifically mentioned the objective of improving connectivity for sea pens and black corals in recommending area closures to the NAFO Commission:

> *Extension to Area Closures 8 and 9 (linking with Area Closures 8, 9 and 12), to provide a more continuous closure to protect sea pens and black coral (Areas 8a and 9a) and improve connectivity*; (NAFO, 2021b).

Further, connectivity is one of the criteria for evaluating closed areas as Other Effective Area-Based Conservation Measures (OECMs). The connectivity work undertaken by the NAFO Scientific Council informed the grouping of separate area closures to protect Large-Sized Sponge in their OECM evaluations (Table 1). With connectivity indices now established, and the subject prominent in international policy, it is hoped that connectivity will play an increased role in decision making in the 2027 review of closed areas to protect VMEs in the NRA.

Acknowledgements

The author acknowledges the extensive contributions of WG-EAFM and its successor WG-ESA in developing the framework for incorporation of connectivity into management advice. She especially acknowledges the contributions of Dr. Pierre Pepin, former chair of WG-ESA, for his direction and insight into operationalizing connectivity for this purpose, and Dr. Mariano Koen-Alonso, for leading the production of the agent-based modeling of sea pens. Dr. Trevor Kenchington provided a review of this manuscript prior to submission.

References

Begg, G. A., Friedland, K. D., and Pearce, J. B. 1999. Stock identification and its role in stock assessment and fisheries management: an overview. *Fisheries Research*, **43**:1–8. https://doi.org/10.1016/S0165-7836(99)00062-4.

Brennan, A., Naidoo, R., Greenstreet, L., Mehrabi, Z., Ramankutty, N., and Kremen, C. 2022. Functional connectivity of the world's protected areas. *Science*, **376 (6597)**: 1101–1104. https://doi.org/10.1126/science.abl8974

Bonanomi, S., Therkildsen, N. O., Retzel, A., Hedeholm, R. B., Pedersen, M. W., Meldrup, D., Pampoulie, C., *et al.,* 2016. Historical DNA documents long-distance natal homing in marine fish. *Molecular Ecology*, **25**: 2727–2734. https://doi.org/10.1111/mec.13580.

Cano, J. M., Shikano, T., Kuparinen A., and Merilä, J. 2008. Genetic differentiation, effective population size and gene flow in marine fishes: implications for stock management. *Journal of Integrated Field Science*, **5**: 1–10.

Carr, M. H., Robinson, S. P. Wahle, C., Davis, G., Kroll, S., Murray, S. Schumacker, E.J., and Williams, M. 2017. The central importance of ecological spatial connectivity to effective coastal marine protected areas and to meeting the challenges of climate change in the marine environment. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **27**: 6–29. https://doi.org/10.1002/aqc.2800

Costello, M. J., and Chaudhary, C. 2017. Marine biodiversity, biogeography, deep-sea gradients, and conservation. *Current Biology*, **27(11)**: R511-R527. https://doi.org/10.1016/j.cub.2017.04.060

Cowen, R. K., and Sponaugle, S. 2009. Larval dispersal and marine population connectivity. *Annual Review of Marine Science*, **1**: 443–466. https://doi.org/10.1146/annurev.marine.010908.163757.

Crooks, K. R., and Sanjayan, M. A. 2006. Connectivity conservation: Maintaining connections for Nature. *In* Connectivity Conservation, pp. 1–20. Edited by K.R. Crooks, and M. Sanjayan. Cambridge University Press, Cambridge. https://doi.org/10.1017/CBO9780511754821.001

Dahms, C., and Killen, S. S. 2023. Temperature change effects on marine fish range shifts: A meta-analysis of ecological and methodological predictors. *Global Change Biology*, **29**: 4459–4479. https://doi.org/10.1111/gcb.16770

DFO. 2016. Evaluation of Hierarchical Marine Ecological Classification Systems for Pacific and Maritimes Regions. DFO *Canadian Science Advisory Secretariat Science Advisory Report* **2016/003**, 19 p. https://waves-vagues.dfo-mpo.gc.ca/library-bibliotheque/365369.pdf.

DFO. 2009. Development of a Framework and Principles for the Biogeographic Classification of Canadian Marine Areas. DFO *Canadian Science Advisory Secretariat Science Advisory Report* 2**009/056**, 17 p. https://waves-vagues.dfo-mpo.gc.ca/Library/338958.pdf.

Doddridge, E. W., and Marshall, D. P. 2018. Implications of eddy cancellation for nutrient distribution within subtropical gyres. *Journal of Geophysical Research: Oceans*, **123**: 6720–6735. https://doi.org/10.1029/2018JC013842.

Estévez-Barcia, D., Roy, D., Vihtakari, M., Gislasson, D., Lindegren, M., Christensen, A., Wheeland, L., Treble, M. Úbeda, J., Nogueira, A., Hedges, K., Láruson, Á. J., Rivera, A. M., Dahle, G., Westgaard, J.-I., Elvarsson, B., Ofstad, L. H., Hallfredsson, E. H., Albert, O. T., Boje, J., and Johansen,

T. 2025. Sex influences the genetic structure of Greenland halibut in the North Atlantic. *Ecology and Evolution*, **15**: e70822. https://doi.org/10.1002/ece3.70822.

FAO. 2009. International Guidelines for the Management of Deep-sea Fisheries in the High Seas. FAO, Rome. 73 p.

Fripiat, F., Martínez-García, A., Marconi, D., Fawcett, S. E., Kopf, S. H., Luu, V. H., Rafter, P.A., Zhang, R., Sigman, D. M., and Haug, G. H. 2021. Nitrogen isotopic constraints on nutrient transport to the upper ocean. *Nature Geoscience*, **14**: 855–861. https://doi.org/10.1038/s41561-021-00836-8

Gustafson, E. J., and Parker, G. R. 1994. Using an index of habitat patch proximity for landscape design. *Landscape and Urban Planning*, **29**: 117–130. https://doi.org/10.1016/0169-2046(94)90022-1

Hanski, I. 1998. Metapopulation dynamics. *Nature*, **396**: 41–49. https://doi.org/10.1038/23876

Hellberg, M. E. 2009. Gene flow and isolation among populations of marine animals. *Annual Review of Ecology, Evolution, and Systematics*, **40**: 291–310. https://doi.org/10.1146/annurev.ecolsys.110308.120223

ICES. 2004. Report of the ICES Advisory Committee on Fishery Management and Advisory Committee on Ecosystems, 2004, Book 1 - Introduction, Overviews, Special Requests, and Regional Advice. ICES Advice Publications. Report. https://doi.org/10.17895/ices.pub.19268660.v1

Jorde, P. E., Søvik, G., Westgaard, J. -I., Albretsen, J., André, C., Hvingel, C., Johansen, T., Sandvik, A. D., Kingsley, M., and Jørstad, K. E. 2015. Genetically distinct populations of northern shrimp, *Pandalus borealis*, in the North Atlantic: adaptation to different temperatures as an isolation factor. *Molecular Ecology*, **24(8)**: 1742–1757. https://doi.org/10.1111/mec.13158.

Kenchington, E., Lirette, C., Sacau, M., Murillo, F. J., and Wang, Z. 2025. Identification of Vulnerable Marine Ecosystems in the NAFO Regulatory Area Combining Kernel Density Analyses, Species Distribution Modeling and Empirical Data. *NAFO Scientific Council Research Document*, SCR Doc. **25/047**, Serial No. **N7693**: 1–105. https://www.nafo.int/PORTALS/0/PDFS/SC/2025/SCR25-047.PDF

Kenchington, E., Murillo, F. J., Lirette, C., Sacau, M., Koen-Alonso, M., Kenny, A., Ollerhead, N., Wareham, V., and Beazley, L., 2019. Kernel density surface modelling as a means to identify significant concentrations of vulnerable marine ecosystem indicators. *PLoS ONE*, **9(10)**: e109365. https://doi.org/10.1371/journal.pone.0109365.

Kenchington, E., Wang, Z., Lirette, C., Murillo, F. J., Guijarro, J., Yashayaev, I., and Maldonado, M. 2018. Connectivity modelling of areas closed to protect Vulnerable Marine Ecosystems in the northwest Atlantic. *Deep Sea Research Part I*, **143**: 85–103. https://doi.org/10.1016/j.dsr.2018.11.007

Kenchington, E. L., Nakashima, B. S., Taggart, C. T., and Hamilton, L. C. 2015. Genetic structure of capelin (*Mallotus villosus*) in the Northwest Atlantic Ocean. *PloS one*, **10(3)**: e0122315. https://doi.org/10.1371/journal.pone.0122315

Koen-Alonso, M., Pepin, P., Fogarty, M. J., Kenny, A., and Kenchington, E. 2019. The Northwest Atlantic Fisheries Organization roadmap for the development and implementation of an ecosystem approach to fisheries: structure, state of development, and challenges. *Marine Policy*, **100**: 342–352. https://doi.org/10.1016/j.marpol.2018.11.025.

Lundberg, J., and Moberg, F. 2003. Mobile link organisms and ecosystem functioning: Implications for ecosystem resilience and management. *Ecosystems*, **6**: 0087–0098. https://doi.org/10.1007/s10021-002-0150-4

McClain, C. R., Signorini, S. R., and Christian, J. R. 2004. Subtropical gyre variability observed by ocean-color satellites. *Deep-Sea Research II: Topical Studies in Oceanography*, **51**: 281–301. https://doi.org/10.1016/j.dsr2.2003.08.002

McRae, B. H., Hall, S. A., Beier, P., and Theobald, D. M. 2012. Where to restore ecological connectivity? Detecting barriers and quantifying restoration benefits. *PLoS ONE*, **7(12)**: e52604. https://doi.org/10.1371/journal.pone.0052604

Monteiro, V. F., Paiva, P. C., and Peres-Neto, P. R. 2017. A quantitative framework to estimate the relative importance of environment, spatial variation and patch connectivity in driving community composition. *Journal of Animal Ecology*, **86**: 316–326. https://doi.org/10.1111/1365-2656.12619

Murillo, F. J., Abalo Morla, S., Downie, A.-L., Lirette, C., Paulin, N., Wang, Z., Devred, E., Clay, S., Sacau, M., Nozères, C., Koen-Alonso, M., Gullage, L., Hayes, V., Caetano, M., Gonçalves, P. and Kenchington, E. 2025. Vulnerable Marine Ecosystems in the NAFO Regulatory Area: Updated Species Distribution Models of Selected Vulnerable Marine Ecosystem Indicators (Large and Small Gorgonian Corals, Erect Bryozoans and Sea Squirts). *NAFO Scientific Council Research Document*, *NAFO SCR Doc.,* **25/035**, Serial No. **N7663**: 62 p.

Murillo, F. J., Downie, A.-L., Abalo Morla, S., Lirette, C., Paulin, N., Wang, Z., Devred, E., Clay, S., Sacau, M., Nozères, C., Koen-Alonso, M., Gullage, L., and Kenchington, E. 2024. Vulnerable marine ecosystems in the Regulatory Area: updated species distribution models of selected vulnerable marine ecosystem indicators (large-sized sponges, sea pens and black corals). *NAFO Scientific Council Research Document*, *NAFO SCR Doc.,* **24/063**, Serial No. **N7601**: 105 p.

Murillo, F. J., Weigel, B., Kenchington, E., and Bouchard Marmen, M. 2020a. Marine epibenthic functional diversity on Flemish Cap (northwest Atlantic) – identifying trait responses to the environment and mapping ecosystem functions. *Diversity and Distributions*, **26(4)**: 460–478. https://doi.org/10.1111/ddi.13026

Murillo, F. J., Kenchington, E., Koen-Alonso, M., Guijarro, J., Kenchington, T. J., Sacau, M., Beazley, L., Rapp, H. T. 2020b. Mapping benthic ecological diversity and interactions with bottom-contact fishing on the Flemish Cap (northwest Atlantic). *Ecological Indicators*, **112**: 106135. https://doi.org/10.1016/j.ecolind.2020.106135

Murillo, F. J., Kenchington, E., Sacau, M., Piper, D. J. W., Wareham, V., and Muñoz, A. 2011. New VME indicator species (excluding corals and sponges) and some potential VME elements of the NAFO Regulatory Area. *NAFO Scientific Council Research Document*, *NAFO SCR Doc.,* **11/73**, Serial No. **N6003**, 20 p.

NAFO. 2025. Northwest Atlantic Fisheries Organization

Conservation and Enforcement Measures 2025. *NAFO COM Doc.*, **25/01** (Revised), Serial No. **N7612**, 207 p.

NAFO. 2024. Report of the 17th Meeting of the NAFO Scientific Council Working Group on Ecosystem Science and Assessment (WG-ESA). *NAFO Scientific Council Summary Document*, *NAFO SCS Doc.*, **24/20**, Serial No. **N7604**, 101 p.

NAFO. 2022a. Report of the 15th Meeting of the NAFO Scientific Council Working Group on Ecosystem Science and Assessment (WG-ESA). *NAFO Scientific Council Summary Document, NAFO SCS Doc.*, **22/25**, Serial No. **N7367**, 90 p.

NAFO. 2022b. Northwest Atlantic Fisheries Organization Conservation and Enforcement Measures 2022. *NAFO Commission Document*, NAFO COM Doc. **22/01**, Serial No. **N7254**, 200 p.

NAFO. 2021a. Report of the 14th Meeting of the NAFO Scientific Council Working Group on Ecosystem Science and Assessment (WG-ESA). *NAFO Scientific Council Summary Document*, *NAFO SCS Doc.*, **21/21**, Serial No. **N7256**, 181 p.

NAFO. 2021b. Report of the NAFO Joint Commission-Scientific Council Working Group on the Ecosystem Approach Framework to Fisheries Management (WG-EAFFM) Meeting. *NAFO Joint Commission–Scientific Council Documen*t, *NAFO COM-SC Doc.* **21/03**, Serial No. **N72094**, 28 p.

NAFO. 2020. Report of the 13th Meeting of the NAFO Scientific Council Working Group on Ecosystem Science and Assessment (WG-ESA). *NAFO Scientific Council Summary Document*, *NAFO SCS Doc.*, **20/23**, Serial No. **N7148**, 270 p.

NAFO. 2019. Report of the 12th Meeting of the NAFO Scientific Council Working Group on Ecosystem Science and Assessment (WG-ESA). *NAFO Scientific Council Summary Document,*, *NAFO SCS Doc.,* **19/25**, Serial No. **N7027**, 135 p.

NAFO. 2018. Report of the 11th Meeting of the NAFO Scientific Council Working Group on Ecosystem Science and Assessment (WG-ESA). *NAFO Scientific Council Summary Document*, *NAFO SCS Doc.,* **18/23**, Serial No. N6900, 112 p.

NAFO. 2016. Report of the 9th Meeting of the NAFO Scientific Council Working Group on Ecosystem Science and Assessment (WGESA). *NAFO Scientific Council Summary Document*, *NAFO SCS Doc.,* **16/21**, Serial No. **N6655**, 105 p.

NAFO. 2015a. Northwest Atlantic Fisheries Organization Conservation and Enforcement Measures 2015. *NAFO Fisheries Commission Document*, *NAFO FC DOC.*, **15/01**, Serial No. **N6409**, 190 p.

NAFO. 2015b. Report of the 8th Meeting of the NAFO Scientific Council Working Group on Ecosystem Science and Assessment (WG-ESA) [Formerly WG-EAFM]. *NAFO Scientific Council Summary Document*, *NAFO SCS Doc.,* **15/19**, Serial No. **N6549**, 176 p.

NAFO. 2014. Report of the 7th Meeting of the NAFO Scientific Council (SC) Working Group on Ecosystem Science and Assessment (WG-ESA) [Formerly SC WG-EAFM]. *NAFO Scientific Council Summary Document*, *NAFO SCS Doc.,* **14/023**, Serial No. **N6410**, 126 p.

NAFO. 2013. Report of the 6th Meeting of the NAFO Scientific Council Working Group on Ecosystem Science and Assessment (WG-ESA) [Formerly WG-EAFM]. *NAFO Scientific Council Summary Document*, *NAFO SCS Doc.,* **13/024**, Serial No. **N6277**, 209 p.

NAFO. 2012. Report of the 5th Meeting of the NAFO Scientific Council Working Group on the Ecosystem Approach to Fisheries Management (WG-EAFM). *NAFO Scientific Council Summary Document*, *NAFO SCS Doc.,* **12/26**, Serial No. **N6137**, 128 p.

NAFO. 2011. Report of the 4th Meeting of the NAFO Scientific Council Working Group on the Ecosystem Approach to Fisheries Management (WG-EAFM). *NAFO Scientific Council Summary Document*, *NAFO SCS Doc.,* **11/22**, Serial No. **N6006**, 126 p.

NAFO. 2010. Report of the 3rd Meeting of the NAFO Scientific Council Working Group on Ecosystem Approach to Fisheries Management (WG-EAFM). *NAFO Scientific Council Summary Document*, *NAFO SCS Doc.,* **10/24**, Serial No. **N5868**, 75 p.

NAFO. 2008. Report of the NAFO Scientific Council Working Group on Ecosystem Approach to Fisheries Management (WG-EAFM). Serial No. N5511. *NAFO Scientific Council Summary Document*, *NAFO SCS Doc.,* **08/10, Serial No. N5511,** 70p.

Palter, J. B., Sarmiento, J. L., Gnanadesikan, A., Simeon, J., and Slater, R. D. 2010. Fueling export production: nutrient return pathways from the deep ocean and their dependence on the Meridional Overturning Circulation. *Biogeosciences*, **7**: 3549–3568. https://doi.org/10.5194/bg-7-3549-2010

Patova, A., Ribeiro, P. A., Murillo, F. J., Riesgo, A., Taboada, S., Pomponi, S. A., Rapp, H. T., Kenchington, E., and Xavier, J. R. 2025. Population genomics and connectivity of *Vazella pourtalesii* sponge grounds of the northwest Atlantic with conservation implications of deep-sea vulnerable marine ecosystems. *Nature Scientific Reports,* **15**: 1540. https://www.nature.com/articles/s41598-024-82462-z.

Pepin, P., Cuff, A., Koen-Alonso, M., and Ollerhead, N. 2010. Preliminary Analysis of the Delineation of Marine Ecoregions on the NL Shelves. *NAFO Scientific Council Research Document*, *NAFO SCR Doc.*, **10/72**, Serial No. **N5871**. 24 p. https://www.nafo.int/Portals/0/PDFs/sc/2010/scr10-072.pdf.

Pepin, P., Higdon, J., Koen-Alonso, M., Fogarty, M., and N. Ollerhead. 2014. Application of ecoregion analysis to the identification of Ecosystem Production Units (EPUs) in the NAFO Convention Area. *NAFO Scientific Council Research Document*, *NAFO SCR Doc.*, **14/069**, Serial No. **N6412**, 13 p. https://www.nafo.int/Portals/0/PDFs/sc/2014/scr14-069.pdf.

Pham, C. K., Murillo, F. J., Lirette, C., Maldonado, M., Colaco, and Kenchington, E. 2019. Removal of deep-sea sponges by bottom trawling in the Flemish Cap area: conservation, ecology and economic assessment. *Nature Scientific Reports*, **9**: 15843. https://doi.org/10.1038/s41598-019-52250-1.

Pineda, J., Hare, J. A., and Sponaugle, S. 2007. Larval transport and dispersal in the coastal ocean and consequences for population connectivity. *Oceanography,* **20**: 22–39. https://doi.org/10.5670/oceanog.2007.27.

Radice, V. Z., Quattrini, A. M., Wareham, V. E., Edinger, E. N., and Cordes, E. E. 2016. Vertical water mass structure in the North Atlantic influences the bathymetric distribution in the deep-sea coral genus *Paramuricea*. *Deep Sea Research Part I: Oceanographic Research Papers*, **116**: 253–263. https://doi.org/10.1016/j.dsr.2016.08.014.

Roques, S., Sévigny, J. M., and Bernatchez, .L. 2002. Genetic structure of deep-water redfish, *Sebastes mentella*, populations across the North Atlantic. *Marine Biology*, **140**: 297–307. https://doi.org/10.1007/s002270100705.

Ruzzante, D. E., Mariani, S., Bekkevold, D., André, C., Mosegaard, H., Clausen, L. A., Dahlgren, T. G., Hutchinson, W. F., Hatfield E. M. C., Torstensen, E., Brigham, J., Simmonds, E. J., Laikre L., Larsson, L. C. Stet, R. J. M., Ryman, N., and Carvalho, G. R. 2006. Biocomplexity in a highly migratory pelagic marine fish, Atlantic herring. *Proceedings of the Royal Society B: Biological Sciences*, **273**: 1459–1464. https://doi.org/10.1098/rspb.2005.3463.

Ruzzante, D. E., Taggart, C. T., and Cook, D. 1999. A review of the evidence for genetic structure of cod (*Gadus morhua*) populations in the NW Atlantic and population affinities of larval cod off Newfoundland and the Gulf of St. Lawrence. *Fisheries Research*, **43**: 79–97. https://doi.org/10.1016/S0165-7836(99)00067-3.

Saura, S., Bertzky, B., Bastin, L., Battistella, L., Mandrici, A., and Dubois, G. 2018. Protected area connectivity: Shortfalls in global targets and country-level priorities. *Biological Conservation*, **219**: 53–67. https://doi.org/10.1016/j.biocon.2017.12.020.

Shanks, A. L., Grantham, B. A., and Carr, M. H. 2003. Propagule dispersal distance and the size and spacing of marine reserves. *Ecological Applications*, **13**: 159–169. https://doi.org/10.1890/1051-0761(2003)013[0159:PDDATS]2.0.CO;2.

Spanowicz, A. G., and Jaeger, J. A. G. 2019. Measuring landscape connectivity: On the importance of within-patch connectivity. *Landscape Ecology*, **34**: 2261–2278. https://doi.org/10.1007/s10980-019-00881-0.

Stratmann, T., Murillo, F. J., Sacau, M., Koen-Alonso, M., and Kenchington, E. 2024. Role of Astrophorina sponges (Demospongiae) in food-web interactions at the Flemish Cap (NW Atlantic). *Marine Ecology Progress Series*, **729**: 99–116. https://doi.org/10.3354/meps14514.

Tischendorf, L., and Fahrig, L. 2000. On the usage and measurement of landscape connectivity. *Oikos*, **90**: 7–19. https://doi.org/10.1034/j.1600-0706.2000.900102.x.

Wang, S., Kenchington, E., Murillo, F. J., Lirette, C., Wang, Z., Koen-Alonso, M., Kenny, A., Sacau, M., and Pepin, P. 2024. Quantifying the effects of habitat fragmentation in deep-sea vulnerable marine ecosystems. *Diversity and Distributions*, **30(5)**: e13824. https://doi.org/10.1111/ddi.13824.

Wang, S., Murillo, F. J., and Kenchington, E. 2022. Climate-change refugia for the bubblegum coral *Paragorgia arborea* in the northwest Atlantic. *Frontiers in Marine Science*, **9**: https://doi/10.3389/fmars.2022.863693.

Wang, S., Kenchington, E., Wang, Z., and Davies, A. J. 2021. Life in the fast lane: Modeling the fate of glass sponge larvae in the Gulf Stream. *Frontiers in Marine Science*, **8**: https://doi.org/10.3389/fmars.2021.701218.

Wang, S., Kenchington, E. L., Wang, Z., Yashayaev I., and Davies, A. J. 2020. 3-D Ocean particle tracking modeling reveals extensive vertical movement and downstream interdependence of closed areas in the northwest Atlantic. *Nature Scientific Reports*, **10**: 21421. https://doi.org/10.1038/s41598-020-76617-x.

Wang, S., Wang, Z., Lirette, C., and Kenchington, E. 2019. Connectivity Between Areas Closed to Protect Vulnerable Marine Ecosystems in the NAFO Regulatory Area using a 3-D Lagrangian Particle Tracking Model. *NAFO Scientific Council Research Document*, *NAFO SCR Doc.*, **19/05**7, Serial No. **N7029**, 15 p.

Watson, J. R., Kendall, B. E., Siegel, D. A., and Mitarai, S. 2012. Changing seascapes, stochastic connectivity and marine metapopulation dynamics. *The American Naturalist*, **180**: 99–112. https://doi.org/10.1086/665992.

Zwanenburg, K., Horsman, T., and Kenchington, E. 2010. Preliminary analysis of biogeographic units on the Scotian Shelf. *NAFO Scientific Council Research Document*, *NAFO SCR Doc.*, **10/06**, Serial No. **N5752.**, 30 p. https://www.nafo.int/Portals/0/PDFs/sc/2010/scr10-006.pdf.

J. Northw. Atl. Fish. Sci., Vol. 57, Special Issue: 27–34
Conference article Publication (Upload) date: 11 Sep. 2026

Developing Guidance for Supporting the Implementation of an Ecosystem Approach to Fisheries Management by Deep-sea RFMOs

Anthony Thompson*[1], Eszter Hidas[2] and Marcelo Vasconcellos[3]
Common Oceans Deep-sea Fisheries Project, Food and Agricultural Organization of the United Nations,
Viale delle Terme di Caracalla, 00153 Rome, Italy

[1]Email: Anthony.Thompson@fao.org
[2]Email: Eszter.Hidas@fao.org
[3]Email: Marcelo.Vasconcellos@fao.org
*Corresponding author

Thompson, A.B., Hidas, E., and Vasconcellos, M. 2026. Developing guidance for supporting the implementation of an ecosystem approach to fisheries management by deep sea RFMOs. *J. Northw. Atl. Fish. Sci.*, **57(2)**: 27–34. https://doi.org/10.2960/J.v57.m757

Abstract

The Ecosystem Approach to Fisheries (EAF) was adopted by the Food and Agriculture Organization of the United Nations (FAO) as a practical framework for fisheries management according to the Code of Conduct for Responsible Fisheries. An EAF recognises that fish and fisheries are part of and dependent upon the entire marine ecosystem and that fisheries management must balance human and ecological considerations in a comprehensive way to achieve sustainable outcomes. This paper elaborates on the inclusion of EAF in international law, the existing guidance to support EAF implementation, and the achievements and challenges remaining for the implementation of the approach by Regional Fisheries Management Organizations (RFMOs) dealing with deep sea fisheries. The implementation of EAF by the RFMOs responsible for demersal and small pelagic species is reviewed and discussed. The authors suggest that future steps should include developing and adopting specific multiannual EAF management and action plans to assist RFMOs in implementing EAF. This should include setting long-term objectives and targets. The process of developing these plans would be enhanced through discussions within joint science-management meetings and workshops within RFMOs.

Keywords: Ecosystem approach, fisheries management, EAF, EAFM, deep-sea fisheries, RFMOs, long-term management plans, targets, reference points

Introduction

The need to account for ecosystem impacts of fishing was first highlighted in international law in article 119 of the 1982 United Nations Convention for the Law of the Sea (UNCLOS, 1982) and reiterated in the 1995 United Nations Fish Stocks Agreement (UNFSA, 1995). The FAO Code of Conduct for Responsible Fisheries (CCRF; FAO, 1995) expanded on the need to maintain important societal benefits associated with fisheries, while ensuring the conservation of stocks and ecosystems. The political commitment to incorporate ecosystem considerations in fisheries management was consolidated in the 'Reykjavík Conference on Sustainable Fisheries in the Marine Ecosystem' in 2001, which has led to the formulation of an ecosystem approach to fisheries (EAF) and its basic principles, based on FAO's perspective (FAO, 2001). The FAO technical guidelines on the ecosystem approach to fisheries describes that: "*An ecosystem approach to fisheries (EAF) strives to balance diverse societal objectives, by taking account of the knowledge and uncertainties of biotic, abiotic and human components of ecosystems and their interactions and applying an integrated approach to fisheries within ecologically meaningful boundaries*" (FAO, 2003, Section 1.2, page 14.). To facilitate implementation of these guidelines, FAO prepared various supplements and tools, including Best Practices in Ecosystem Modelling (FAO, 2008), and The Human Dimension to EAF (FAO, 2009a). These have been further supported by FAO developing an EAF Toolbox, an Implementation Monitoring Tool, and a comprehensive e-learning package (FAO, 2012, 2021a, 2023). At the core of FAO's ecosystem approach is the recognition that fisheries management must balance human needs with ecological sustainability, weighing the trade-offs to ensure long-term use.

Seven RFMOs[1] and the Commission for the Conservation

1 General Fisheries Commission for the Mediterranean (GFCM); Northwest Atlantic Fisheries Organization (NAFO); North East Atlantic Fisheries Commission (NEAFC); North Pacific Fisheries Commission (NPFC); South East Atlantic Fisheries Organization (SEAFO); Southern Indian Ocean Fisheries Agreement (SIOFA); South Pacific Regional Fisheries Management Organization (SPRFMO).

of Antarctic Marine Living Resources (CCAMLR) manage demersal and small pelagic finfish and shellfish species in areas beyond national jurisdiction (ABNJ). They are collectively referred to as deep sea RFMOs (dsRFMOs) from here on. Half of them (GFCM, NAFO, SIOFA and SPRFMO) make direct reference to the application of the ecosystem approach to fisheries in their convention or agreement texts. For instance, Article 8 of the Agreement establishing the GFCM recognizes as one of the functions of the Commission "*to adopt multiannual management plans applied in the totality of the relevant subregions based on an ecosystem approach to fisheries…*". Likewise, Article 4(a) of the SIOFA Agreement includes as part of the general principles that "*measures shall be adopted on the basis of the best scientific evidence available to ensure the long-term conservation of fishery resources, taking into account the sustainable use of such resources and implementing an ecosystem approach to their management*". All the deep sea RFMOs (dsRFMOs) are mandated under UNCLOS and UNFSA to ensure that they consider the effects of fishing on the wider ecosystem and make explicit reference to this in their agreements. For instance, Article 4(2)(c) of NEAFC's Convention indicates that in making recommendations the Commission shall "*take due account of the impact of fisheries on other species and marine ecosystems, and in doing so adopt, where necessary, conservation and management measures that address the need to minimise harmful impacts on living marine resources and marine ecosystems*".

The interpretation of what an ecosystem approach to fisheries management (EAFM) entails, however, differs among the Conventions of dsRFMOs. Most commonly, it is interpreted to include ecological considerations such as non-target and associated or dependent species, as well as the general obligation to protect and preserve the marine environment, for example, as written into the SPRFMO Convention (see Art. 3, Para 1(a)(ii); SPRFMO, 2022). However, some dsRFMOs, such as GFCM, also include social and economic considerations (Art. 2, Para. 2; GFCM, 2014) and NEAFC note that their fisheries should provide sustainable economic, environmental and social benefits (Art. 2; NEAFC, 2006). CCAMLR, formed under the Antarctic Treaty (1959), has a wider ecological remit than the dsRFMOs.

There is a tendency to regard EAFM as a scientific exercise, with scientific committees providing advice to the managers on, for example, reducing impacts on vulnerable taxa like seabirds and deepwater sharks, and to protect fragile benthic habitats from bottom fishing such as vulnerable marine ecosystems. Instead, EAFM is wider and aims to improve fishery management processes by applying risk management principles to determine management actions appropriate to the level of risk posed by the identified issues, including ecological, socioeconomic, and governance issues affecting the sustainable use of resources (FAO, 2012; Fletcher, 2020).

Much of these are already considered by the dsRFMOs but not necessarily recognized as part of an EAFM. A greater understanding of an EAFM approach within each dsRFMO would be supported by the development of guidance documents. This could be achieved in joint science-management fora to ensure equal participation of the constituent bodies and to lessen the time taken for formal communication between these bodies (which typically meet only once a year). This would also improve implementation, increase transparency, and provide a wider appreciation of the work of the dsRFMOs.

This paper provides the rationale for the development of guidance for supporting the implementation of EAFM by dsRFMOs. It provides an overview of existing guidance available on the implementation of EAFM, highlights key gaps in implementation, and makes the case for the development of further guidance on the implementation of EAFM specific to dsRFMOs. An extended version of this paper was provided as background information and direction to the Symposium "*Applying the Ecosystem Approach to Fisheries Management in the ABNJ*" held at FAO, Rome on 11–13 March 2025 and formed the basis for an introductory presentation (Thompson, 2025).

Existing guidance for applying EAFM to deep sea fisheries in ABNJ

The FAO EAF Technical Guidelines and the supplements

The FAO 2003 Technical Guidelines for the Ecosystem Approach to Fisheries (EAF Guidelines for here on) was developed to supplement and provide a practical approach to implement the CCRF. They also support UNCLOS by providing guidance to States by elaborating on "*In determining the allowable catch and establishing other conservation measures for the living resources in the high seas, States shall: (a) take measures which are designed, on the best scientific evidence available to the States concerned, to maintain or restore populations of harvested species at levels which can produce the maximum sustainable yield, as qualified by relevant environmental and economic factors, including the special requirements of developing States, and taking into account fishing patterns, the interdependence of stocks and any generally recommended international minimum standards, whether subregional, regional or global; (b) take into consideration the effects on species associated with or dependent upon harvested species with a view to maintaining or restoring populations of such associated or dependent species above levels at which their reproduction may become seriously threatened.*" (UNCLOS, 1982, Art. 119; see also FAO, 1995, Para. 6.1 & 6.2).

The EAF Guidelines also places the requirements within UNCLOS in a more holistic framework recognising that fisheries are made up of ecological, social and economic

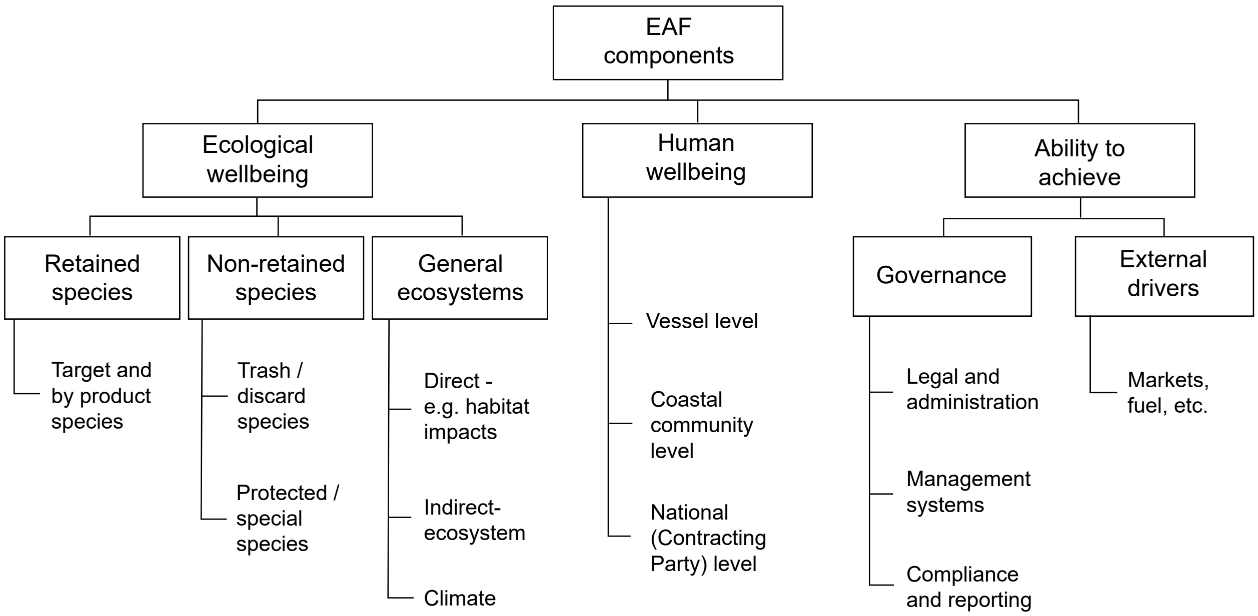


Fig. 1. The 13 key EAF components. Redrawn from Figure 2 of Fletcher (2020).

dimensions and that effective implementation requires a well-structured governance system. Further, greater realisation regarding human impacts on the environment was developing quickly at the turn of the century, promoted by Agenda 21 (UNCED, 1992), the Reykjavik Declaration (FAO, 2001), and the Earth Summit (WSSD, 2002), making the EAF Guidelines timely. However, the EAF Guidelines have no legal status and are an aid to help managers, scientists, and various stakeholder groups, promoting an understanding of the importance of EAF in fisheries management and provide guidance on implementation.

EAF is promoted by FAO as a risk-based management planning process that accounts for issues across different dimensions of sustainable development: environmental protection, economic development, and social wellbeing. In terms of EAFM, this is expressed as the dimensions or component groups: ecological well-being, human well-being and the ability to achieve (Fig. 1). Typically, although not always, dsRFMOs are mandated to manage the ecological dimension that includes retained species, non-retained species and fisheries impacts more generally on the ecosystem. There have been calls to consider more explicitly the implications of external drivers of deep-sea fisheries (DSF), such as climate-change and cross-sectoral interactions. On the other hand, the consideration of human dimensions[2] is generally outside of the mandate of the dsRFMOs and so is rarely discussed, but they are important to national delegations and discussed internally and can drive the positions of individual Contracting Parties at dsRFMO meetings.

2 The human dimension includes social, cultural, economic, political and institutional processes and factors (FAO, 2009a)

In relation to governance, the EAF Guidelines stress the importance of stakeholder engagement which operates at two separate but overlapping levels in dsRFMOs. Engagement starts with national discussions. This usually involves discussions with the fishing industry, which can typically address various socioeconomic interests and objectives, and increasingly over the last 20 years has included environmental groups concerned with biodiversity conservation, and the achievement of the Sustainable Development Goals (SDGs) and Global biodiversity Framework (GBF) targets. The RFMO's scientific advice is also considered nationally, and together these cement the Contracting Party positions. These all underpin the implementation of EAF. The next level of engagement occurs at the RFMO meetings, and particularly at the decision-making management committee level. Here, any national positions are then "translated" into biological or ecological proposals for developing and adopting fisheries measures for stock management (effort or catch control, etc.) and reducing impacts (gear modifications, seasonal, temporal and permanent area closures, etc.).

FAO has produced several supplements to the EAF Guidelines, covering both topics of general relevance to all fisheries and fishery-specific applications, such as bottom fisheries in the high seas (discussed in the next section). Among the general supplements, key examples include: FAO (2008), which addresses the use of ecosystem models to inform management decisions; FAO (2009a), which covers the human dimensions of EAF, including social, economic, and institutional aspects; FAO (2012), a toolbox guiding practitioners through the main planning and implementation steps; FAO (2021a), a tool for tracking progress in EAF implementation; and FAO (2021b), a legal diagnostic tool to help countries assess how well their national policies and laws align with EAF. In addition, FAO has developed a digital hub and a series of e-learning courses on EAF principles and tools to further support global uptake (https://www.fao.org/fishery/en/eaf-net). The EAF Guidelines and its supplements note the importance of applying the precautionary approach when implementing EAF.

FAO Deep-sea Fisheries Guidelines

The *International Guidelines for the Management of Deep-sea Fisheries in the High Seas* (DSF Guidelines) (FAO, 2009b) were developed at the request of the twenty-seventh session of the Committee on Fisheries (COFI) of FAO, in order to assist States and RFMOs in sustainably managing DSF and in implementing the United Nations General Assembly (UNGA) Resolution 61/105, paragraphs 76–95, concerning responsible fisheries in the marine ecosystem. They are arranged in five sections: scope and principles, key concepts, governance and management, management and conservation, and special requirements of developing states.

The DSF Guidelines were developed in accordance with an EAF and cover different dimensions, in particular the ecological dimensions (retained species, non-retained species, and general ecosystems) and the human dimension in terms of governance and management (data reporting and assessment, enforcement and compliance, management measures and plans). They also note the importance of collecting socio-economic data (*e.g.* on catches, value of landings and employment in the harvesting and processing sectors) by States and the need to develop specific guidelines for this purpose.

The greater part of the DSF Guidelines is given to the protection of vulnerable marine ecosystems from significant adverse impacts that may be caused by fishing with bottom contact gears. These are very slow-growing and structure-forming benthic habitats prone to physical damage from fishing gears and are protected typically by closures to bottom fishing gears.

The long-term sustainable management of demersal fish stocks and the reduction of bycatch is also an important part of the DSF Guidelines and clearly falls under an EAF concept. RFMOs should adopt sets of measures to respond to short-term situations and be guided by defined long-term multi-annual management objectives. The measures should be tailored on a case-by-case basis to the characteristics of each fishery using biological reference points set at levels that ensure, at a minimum, that fish stocks are harvested at levels that are sustainable in the long term.

Current gaps for implementing EAF-compatible management systems by dsRFMOs

There have been two recent reviews of the implementation of EAFM by dsRFMOs in the ABNJ.

Review of the implementation of EAFM by dsRFMOs

The first review by Fletcher (2020) systematically went through 13 of FAO's EAFM components that sit within three component groups (ecosystem wellbeing, human wellbeing, and the ability to achieve) in a desktop study using publicly available web-based information to assess implementation by the dsRFMOs. Results showed that the governance component was well covered, and the ecological component was mostly to partially covered. The top scorer within the ecological wellbeing group related to the retained species, since this has been considered as the primary focus of the RFMO mandates as given in their Conventions. The other four components in this group related to impacts (non-retained species, "special" species, direct fishing effects, and cumulative ecosystem effects), which is a more recent and growing focus of the dsRFMOs. CCAMLR's mandate covers all aspects of the ecosystem and so it covers these more directly. Climate effects were placed in two components and had low scores mainly owing to challenges in how it should be implemented. The remaining three components under consideration all had low scores and all are considered outside of the remit of the dsRFMOs. Nevertheless, these are addressed at the national level, but this was outside the scope of this review.

Fletcher (2020) found no comprehensive assessments or documentation from the available dsRFMO public information that guide their EAF implementation. Yet, his review showed that many aspects of EAF have already been covered by the dsRFMOs. He noted that the critical steps required for developing a 'compliant' EAF management plan and overall system of governance is to outline all the potential EAF-related actions and assess the risks and opportunities systematically. Such documentation provides the best basis to determine relative priorities and what level (if any) of management intervention is required. The significant efforts that each of the dsRFMOs has already made could easily be integrated into a fully EAF-compliant system.

He also noted that most of the dsRFMOs have delegated dealing with EAF to a science-based working group. Yet implementing an EAF approach are the responsibilities of both the managers and scientists. Adopting an EAF approach should be an overarching management strategy

Table 1. Average level of implementation of each of the EAF components by dsRFMOs.

Group	EAF Component	Score*
Ability to achieve	Compliance, reporting and review	2.6
	Management systems	2.0
	Legal and administration	2.5
	Non-environmental external drivers	1.3
Ecological wellbeing	Retained species	2.4
	Non-retained species	2.0
	"Special" species	2.1
	Direct fishing effects	2.1
	Cumulative ecosystem effects	1.6
	Climate	1.3
Human wellbeing	National social/economic	1.0
	Vessel social/economic	0.6

* 1= Partly, 2 = Mostly, and 3 = Fully implemented. Values in this table are the average scores across the seven dsRFMOs and CCAMLR. Compiled from Figure 20 of Fletcher (2020).

within each dsRFMO, and should result in the generation of clear, holistic assessments that would facilitate the development of clearly articulated and integrated long-term management plans.

Review of the implementation of the DSF Guidelines by dsRFMOs

The second review was by Thompson and Reid (2024) on the implementation of the DSF Guidelines by dsRFMOs. The DSF Guidelines encompass many aspects of EAF including retained species, non-retained species, and ecosystem considerations by way of the protection of vulnerable marine ecosystems (VMEs). The methods of analysis were similar to those used by Fletcher but had more categories which reflected the greater operational detail in the DSF Guidelines (Table 2).

The conclusions support Fletcher's (2020) findings but provide a greater insight into the details of implementation. The indicators in the monitoring, control and surveillance group were well implemented, as were those indicators in the VME group for protecting VMEs from significant adverse impacts (SAIs). This reflects the considerable effort that dsRFMOs have put into these indicators, though they still have their challenges, but at least most of the control measures are in place.

The implementation of the fishery assessments group was more variable and reflects the immediate objectives of managing the targeted fisheries in the short-term using control measures (note that the effectiveness of these measures was not assessed). This was typically consistent with the scientific advice on these fisheries where there are projections over the next 2–4 years. The fish stock biomass was also known for only some of the major targeted stocks and reflects the difficulty in undertaking these assessments. However, it is quite possible to manage a stock sustainably without knowing the stock biomass.

Less well implemented were the use of reference points and long-term management plans; both are integral to EAF and both help guide management towards achieving longer term objectives. Non-target bycatch limits are another aspect that requires further improvement. This includes minor species that are landed, fish species of no commercial value that are discarded, and certain vulnerable and protected groups like deepwater sharks and seabirds. Under an EAF, it is clearly important to know the total removals from the system and to set limits where appropriate for conservation purposes.

Summary of gaps in EAFM implementation by dsRFMOs

The implementation of the International Guidelines for the Management of Deep-sea Fisheries in the High Seas adopted in 2008 (FAO, 2009b) was reviewed by looking at 18 indicators grouped under fishery assessment, VMEs and monitoring, control and surveillance (MCS) (Thompson and Reid, 2024). The dsRFMOs have implemented many aspects of EAFM that extend well beyond their normal claims of "*We apply EAFM by protecting VMEs*" and the like. As detailed above, EAFM includes the RFMO work on retained species for sustainable fisheries where dsRFMOs score highly. The dsRFMOs also have a well-defined governance system and MCS procedures are operational. There are some gaps that would help with

Table 2. Average level of implementation of each of various indicators in the DSF Guidelines by dsRFMOs.

Group	Indicator	Implementation score*
Monitoring, control and surveillance (MCS)	On-board observers	40
	Verification	67
	Haul level catch reporting	67
	IUU vessel list	100
	Fishing vessel list	100
	VMS	75
Fishery assessments	Target TAC set	85
	Target biomass known	37
	Reference points and management plans	20
	Non-target bycatch limits	37
	Exploratory fishing protocol	75
	Existing bottom fishing area	60
Vulnerable Marine Ecosystems (VMEs)	Reporting encounters	25
	Threshold	87
	Avoiding SAIs	87
	VME closures	75
	Identification guide	75
	VME and SAI defined	100

* Percent of dsRFMOs implementing the activity – 100 percent is fully implemented. Compiled from Figure 8 of Thompson and Reid (2024) .

the understanding and implementation of EAFM. These include:

General aspects

- An EAFM global guidance document to build on existing documents but focused on dsRFMOs.
- Outlining all EAF-related issues and associated risk assessments.
- Long-term management plans and objectives.
- Greater involvement of fisheries managers to guide EAFM process.
- Considering working with dsRFMOs Contracting Parties on socio-economic components of EAFM.

Specific aspects

- Bycatch (retained and discarded) recording and associated bycatch limits.
- Improved risk assessments on vulnerable species.
- Cumulative ecosystem effects, including from fishing, mineral extractions and climate change.
- Greater development of species specific and ecosystem indicators and reference points.

A way forward for implementing EAF in dsRFMOs

An EAF concept brings together the various components of fisheries (ecological, social and economic) and identifies the institutional conditions required for its implementation. When considering dsRFMOs specifically, we note that:

- Generic technical guidelines on EAF (mainly from FAO) and specific guidance applicable to DSF are available to support a greater alignment of dsRFMOs with an EAFM.
- Many aspects of EAF are already implemented, but an overall management plan is lacking in most dsRFMOs.
- The management and science committees within

dsRFMOs deal almost exclusively with the ecological component of EAF. Whereas their members nationally are also concerned with the social and economic aspects of fisheries.

- While our understanding of species interactions and ecosystem dynamics continues to improve, these remain complex areas requiring sustained research and funding.
- The best available information should be used, and precaution applied where risks are high or knowledge is limited. The EAF and the precautionary approach emphasize that uncertainty or lack of knowledge is not a reason for inaction.
- And finally, climate change is affecting the ABNJ, which may not significantly impact the short-term stock assessments, but will affect longer-term ecosystem, social and economic conditions. It will also increase uncertainty. Long-term targets and goals are still required, but they become harder to quantify and adopt.

The conclusions from the above indicate that we already have much of the information required to implement EAFM in dsRFMOs. The EAFM symposium convened groups of scientists, managers, academics, and other stakeholders from around the world. There was impressive dedication to implement EAF from all participants present, but there is a need for a more consolidated approach by scientists and managers within dsRFMOs. We believe that one way forward to enhance implementation is for each dsRFMO to develop and adopt multiannual long-term EAF management and action plans, based on best available knowledge and guided by appropriate science-management dialogues, to address priorities and critical gaps for the sustainability of deep-sea fisheries in the high seas. This can be a concrete way to consolidate knowledge, recognize and give visibility to ongoing developments and increase transparency about management objectives and actions. The guidance provided by FAO, past, present and future, can help dsRFMOs develop their regionally specific long-term management plans.

The ecosystem approach is increasingly recognized as a long-term commitment in ocean governance, reflected in major international frameworks such as UNCLOS and the 1994 Agreement relating to the Implementation of Part XI of UNCLOS (ISA, 1994), the Convention on Biological Diversity (CBD, 2022) and its Kunming-Montreal Global Biodiversity Framework (GBF), and the recently adopted Agreement on Biodiversity Beyond National Jurisdiction (BBNJ, 2023). Since the early 2000s, international organizational and stakeholder engagement in ABNJ has expanded markedly, requiring that these evolving global instruments and targets be incorporated into, or explicitly linked with, fisheries management, including through the application of EAF as a sector-specific implementation of the broader ecosystem approach.

Acknowledgements

The authors wish to thank FAO for hosting the symposium and especially those staff who provided audio-visual support and translated the broadcast into French and Spanish. Gwyneth Byrd and Amanda Santos of the Deep-sea Fisheries Project, FAO, supported the administrative aspects and organised the posters for the symposium. The authors also wish to thank two anonymous referees for making helpful suggestions to improve the paper.

Disclaimer

The views expressed in this information product are those of the authors and do not necessarily reflect the views or policies of FAO, NAFO, ICES or any of the other organisations involved in the EAFM Symposium held at FAO HQ, Rome, on 11–13 March 2025.

References

Antarctic Treaty. 1959. The Antarctic Treaty. 53 p. https://documents.ats.aq/ats/treaty_original.pdf

BBNJ. 2023. Agreement under the United Nations Convention on the Law of the Sea on the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction. UNGA A/CONF.232/2023/4. https://digitallibrary.un.org/record/4013344/files/A_CONF.232_2023_4-EN.pdf

CBD. 2022. Kunming-Montreal global biodiversity framework. https://www.cbd.int/gbf

FAO. 1995. Code of Conduct for Responsible Fisheries. Rome, FAO. 41 p. https://www.fao.org/3/v9878e/V9878E.pdf

FAO. 2001. Reykjavik Declaration on Responsible Fisheries in the Marine Ecosystem. IN. The Reykjavik Conference on Responsible Fisheries in the Marine Ecosystem. Reykjavik, Iceland, 1–4 October 2001. Appendix 1, C2001/INF/25. https://openknowledge.fao.org/server/api/core/bitstreams/8f2c9c9d-9d36-49eb-a479-30a76c73b505/content/y2211e.htm

FAO. 2003. The ecosystem approach to fisheries. *FAO Technical Guidelines for Responsible Fisheries*, No. 4, Suppl. 2. Rome, FAO. 112 p. https://www.fao.org/3/a-y4470e.pdf

FAO. 2008. Fisheries management. 2. The ecosystem approach to fisheries. 2.1 Best practices in ecosystem modelling for informing an ecosystem approach to fisheries. *FAO Fisheries Technical Guidelines for Responsible Fisheries*, No. 4, Suppl. 2, Add. 1. Rome, FAO. 78 p. https://www.fao.org/3/a-i0151e/i0151e00.pdf

FAO. 2009a. Fisheries management. 2. The ecosystem approach to fisheries. 2.2 Human dimensions of the ecosystem approach to fisheries. *FAO Technical Guidelines for Responsible Fisheries*, No. 4, Suppl. 2, Add. 2. Rome, FAO. 88 p. https://www.fao.org/3/i1146e/i1146e.pdf

FAO. 2009b. International Guidelines for the Management of

Deep-sea Fisheries in the High Seas. Rome, FAO. 92 p. https://www.fao.org/3/i0816t/I0816T.pdf

FAO. 2012. EAF Toolbox: The ecosystem approach to fisheries. Rome, FAO. 172 p. https://openknowledge.fao.org/server/api/core/bitstreams/7ee8ec8d-703b-4341-895a-6331ef44e635/content

FAO. 2021a. Ecosystem approach to fisheries implementation monitoring tool – A tool to monitor implementation of the ecosystem approach to fisheries (EAF) management. User manual. Rome, FAO. 80 p. https://doi.org/10.4060/cb3669en

FAO. 2021b. A diagnostic tool for implementing an ecosystem approach to fisheries through policy and legal frameworks. Rome. https://doi.org/10.4060/cb2945en

FAO. 2023. Ecosystem approach to fisheries: Introduction. FAO e-learning Academy, Rome, FAO. https://elearning.fao.org/course/view.php?id=784

Fletcher, W.J. 2020. A review of the application of the FAO ecosystem approach to fisheries (EAF) management within the areas beyond national jurisdiction (ABNJ). Rome, FAO. 303 p. https://doi.org/10.4060/cb1509en

GFCM. 2014. Agreement for the Establishment of the General Fisheries Commission for the Mediterranean. Rome, FAO. 15 p. https://gfcmsitestorage.blob.core.windows.net/website/Basic%20Texts_Agreement/GFCM_Agreement-e.pdf

ISA. 1994. The International Seabed Authority. https://isa.org.jm/

NEAFC. 2006. Convention on Future Multilateral Cooperation in North-East Atlantic Fisheries. London, NEAFC. 11 p. https://www.neafc.org/system/files/Text-of-NEAFC-Convention-04.pdf

SPRFMO. 2022. Convention on the Conservation and Management of High Seas Fishery Resources in the South Pacific Ocean. Wellington, SPRFMO. 52 p. https://sprfmo.int/assets/Basic-Documents/Convention-and-Final-Act/SPRFMO-Convention-2023-update-12May2023.pdf

Thompson, A. B. 2025. Introduction to the symposium. Presentation to "Applying the Ecosystem Approach to Fisheries Management in the ABNJ" symposium. Day 1, 09:00. 13 slides. https://eafm-symposium.nafo.int/Portals/3/Documents/Discussions/1.0-Thompson-Intro-Final-Rev.pdf

Thompson, A. B., and Reid, K. 2024. Review of the implementation of the International Guidelines for the Management of Deep-sea Fisheries in the High Seas. FAO Fisheries and Aquaculture Technical Paper, No. 703. Rome, FAO. 342 p. https://doi.org/10.4060/ca7692en

UNCED. 1992. AGENDA 21 - United Nations Conference on Environment & Development Rio de Janerio, Brazil, 3 to 14 June 1992. 351 p. https://sdgs.un.org/sites/default/files/publications/Agenda21.pdf

UNCLOS. 1982. United Nations Convention on the Law of the Sea. United Nations, New York. 202 p. https://www.un.org/depts/los/convention_agreements/texts/unclos/unclos_e.pdf

UNFSA. 1995. Agreement for the Implementation of the Provisions of the United Nations Convention on the Law of the Sea of 10 December 1982 relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks. United Nations, New York. 40 p. https://www.un.org/oceancapacity/sites/www.un.org.oceancapacity/files/files/Projects/UNFSA/docs/unfsa_text-eng.pdf

WSSD. 2002. Report of the World Summit on Sustainable Development Johannesburg, South Africa, 26 August–4 September 2002. United Nations, New York. 173 p. https://digitallibrary.un.org/record/478154/files/A_CONF.199_20-EN.pdf

J. Northw. Atl. Fish. Sci., Vol. 57, Special Issue: 35–53
Publication (Upload) date: 11 Sep. 2026
Conference article

Standards to Inform an Ecosystem Approach to Deep-sea Bottom Fisheries Management in the High Seas: Examples from the South Pacific Ocean

Jordi Tablada[1]*, Shane W. Geange[1], Alexander Arkhipkin[2], Andrew Biggerstaff[2], Karen Tunley[2], Martin Cryer[3], Trent Timmiss[4], Jan Geert Hiddink[5], Lee Georgeson[6], and Ashley A. Rowden[7,8]

[1]Department of Conservation, Wellington, New Zealand
[2]Fisheries New Zealand, Wellington, New Zealand
[3]Fisheries New Zealand, Nelson, New Zealand
[4]Australian Bureau of Agriculture Resource Economics and Science, Canberra, Australia
[5]School of Ocean Sciences, Bangor University, United Kingdom
[6]Australian Government Department of Climate Change, Energy, the Environment and Water, Canberra, Australia
[7]Earth Sciences New Zealand, Wellington, New Zealand
[8]Victoria University of Wellington, Wellington, New Zealand
*Corresponding author jtablada@doc.govt.nz

Tablada, J., Geange, S.W., Arkhipkin, A., Biggerstaff, A., Tunley, K., Cryer, M., Timmiss, T., Hiddink, J.G., Georgeson, L., and Rowden, A.A. 2026. Standards to inform an ecosystem approach to deep-sea bottom fisheries management in the High Seas: examples from the South Pacific Ocean. *J. Northw. Atl. Fish. Sci.,* **57(2)**: 35–53. https://doi.org/10.2960/J.v57.m760

Abstract

The South Pacific Regional Fisheries Management Organisation (SPRFMO) Convention requires consideration of risks and impacts as part of an ecosystem approach to fisheries management. In SPRFMO, assessments of the impact of demersal fisheries are guided by the Bottom Fishery Impact Assessment Standard and the Encounter Review Standard. The Bottom Fishery Impact Assessment Standard describes a standardised approach for assessing cumulative impacts of bottom fishing, including for new and exploratory fisheries, on Vulnerable Marine Ecosystems (VMEs), deep-sea fish stocks and marine mammals, reptiles, seabirds and other species of concern. The Encounter Review Standard describes responsibilities when reviewing potential encounters with VMEs, which occur when bycatch of VME indicator taxa (*e.g.*, stony corals) in any trawl tow reach or exceed predefined encounter thresholds, resulting in temporary suspension of fishing in the encounter area. Both the Bottom Fishery Impact Assessment Standard and the Encounter Review Standard are periodically updated to reflect best practice, alignment with the FAO International Guidelines for the Management of Deep-sea Fisheries in the High Seas, and account for the best available scientific information required to protect VMEs from significant adverse impacts while ensuring sustainable management of bottom fisheries. Here, we detail the structure and function of these two standards, their periodic updates to reflect best practice and scientific knowledge, and their role in operationalising an ecosystem approach. We also discuss gaps, uncertainties, and potential future improvements for these standards, including the need for better integration of cumulative impacts (such as climate change and cross-sectoral pressures) into the standards, and the usefulness of having universal assessment standards for RFMOs. Through the examples from SPRFMO, we illustrate the importance and role standards can play in achieving sustainable, science-based management of deep-sea fisheries in areas beyond national jurisdiction.

Keywords: benthic impact assessments; deep-sea fisheries; ecosystem approach; risk assessment; significant adverse impacts; vulnerable marine ecosystems; regional fisheries management organisations.

Introduction

Until the early-to-mid 2000s, deep-sea fisheries across the South Pacific Ocean were mainly regulated by the domestic provisions imposed on fishing operators by flag States. In 2006, Australia, Chile and New Zealand initiated consultations among relevant States to address key gaps in the international conservation and management of fisheries resources, as well as the protection of the broader marine environment in the South Pacific high seas. Shortly after, the United Nations General Assembly (UNGA) adopted Resolution 61/105, which called upon the Regional

Fisheries Management Organisation (RFMO) bodies to:

> "*83 (a) To assess, on the basis of the best available scientific information, whether individual bottom fishing activities would have significant adverse impacts on vulnerable marine ecosystems, and to ensure that if it is assessed that these activities would have significant adverse impacts, they are managed to prevent such impacts, or not authorized to proceed;*"

Key elements of Resolution 61/105 included undertaking bottom fishing impact assessments to determine whether bottom fishing would risk exposing vulnerable marine ecosystems (VMEs) to significant adverse impacts (SAIs), identifying VME locations, establishing move-on rules and protocols, ensuring the sustainable management of deep-sea fish stocks, and establishing effective monitoring, control and surveillance of fishing operations and their environmental impacts.

In 2009, the FAO published the International Guidelines for the Management of Deep-Sea Fisheries in the High Seas (FAO, 2009), hereafter referred to as the Deep-Sea Fisheries Guidelines. These guidelines provided recommendations on governance and management frameworks of deep-sea fisheries aimed at ensuring long-term conservation and sustainable use of marine living resources in the deep-sea, while preventing SAIs on VMEs. These guidelines provided specific advice on the characteristics which should be used to identify VMEs, and a definition of SAIs (both of which were not provided by previous UNGA Resolution 61/105). The Deep-Sea Fisheries Guidelines have been a transformational document widely used by Regional Fisheries Management Organisations (RFMOs) engaging with demersal fisheries to the current day. Shortly after, in 2011, the UNGA adopted Resolution 66/68, reaffirming earlier Resolutions on sustainable fisheries and calling on States and RFMOs to apply a precautionary approach and to implement the Deep-Sea Fisheries Guidelines.

The Deep-Sea Fisheries Guidelines and relevant UNGA Resolutions informed the development of interim measures during international consultations on the establishment of the South Pacific Regional Fisheries Management Organisation (SPRFMO). These measures included early drafts of the Bottom Fishery Impact Assessment Standard (BFIAS) and the Standards for the Collection, Reporting, Verification and exchange of Data (*e.g.*, SPRFMO, 2009b), hereafter referred to as Data Standards. The initial BFIAS developed for SPRFMO aimed to establish a minimum standard for assessing the potential impacts of proposed bottom fishing activities on VMEs and deep-sea fish stocks. Complementing this, the Data Standards set out requirements for Member States to submit fishing effort and catch data, including the mandatory reporting of accidental catches of any sensitive benthic species, particularly vulnerable or habitat-forming species such as sponges, sea-fans or corals. To the present day, there is no universal benthic impact assessment standard being followed across international resource management and conservation bodies (including RFMOs), but SPRFMO and the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) (Sharp *et al*, 2009) were among the first such bodies to develop their own benthic impact assessment standards (DOSI, 2022; Kaikkonen *et al*., 2024).

SPRFMO was officially established in 2012. Australia and New Zealand were the only Members engaging in established bottom fisheries at that time. Based on early international agreements, UNGA Resolution 61/105 and the Deep-Sea Fisheries Guidelines, these two Members drove the implementation of the management arrangements that would satisfy the varied international obligations and objectives as manifested through the SPRFMO Convention and related non-binding instruments. This work led to the first Conservation and Management Measure (CMM) for the Management of Bottom Fishing in the SPRFMO Convention Area (Fig. 1) being in force in 2014 (SPRFMO, 2014).

In 2016, the UNGA adopted Resolution 71/123, which emphasised the importance of strengthening procedures for carrying out, reviewing and evaluating impact assessments, taking into account individual collective and cumulative impacts, and ensuring that any measures are based on best available scientific information, and adopt an ecosystem approach (Garcia and Cochrane, 2005). The 2016 Resolution also highlighted inconsistencies in implementation of the earlier Resolutions on sustainable fisheries across RFMOs. Recognising that implementation of SPRFMO bottom fishing measures by Members was sub-optimal, the SPRFMO Commission supported efforts led by Australia and New Zealand to initiate discussions aimed at revising the bottom fishing measure. The objective was to establish consistent management arrangements for all Members engaged in established bottom fisheries in the SPRFMO Convention Area. As a result of further work led by Australia and New Zealand and supported by other Members including the Cook Islands, the European Union (EU) and the United States (US), a comprehensive package of measures designed to assess, monitor and control bottom fisheries were developed and compiled into an updated CMM for the Management of Bottom Fishing in the SPRFMO Convention Area, hereafter referred to as CMM03 (SPRFMO, 2019b). Key measures provided by CMM03 included the designation of three different types of Management Areas to allow for bottom fisheries (based on fishing gear: bottom line; midwater trawl; and bottom trawl), the design of areas in which bottom fishing could be conducted using a spatial prioritisation approach (Cryer *et al*., 2018; Grantham *et al.*, 2024; Rowden *et al*., 2026), and a VME encounter protocol and move-on rule to be

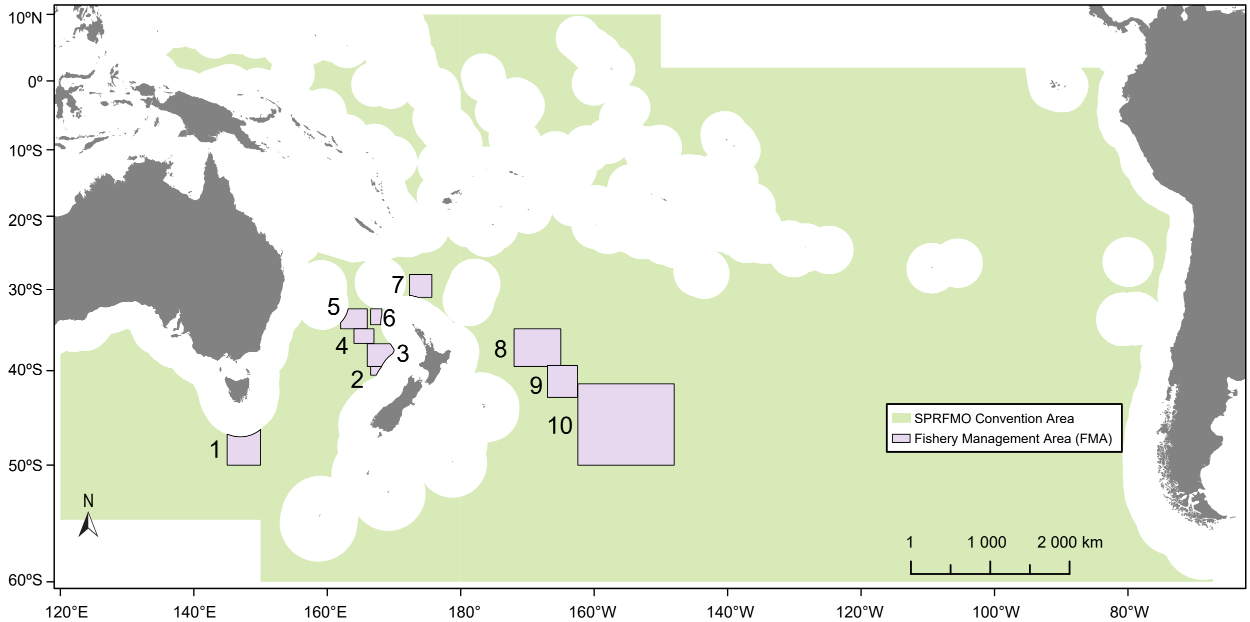


Fig. 1. SPRFMO Convention Area (in green) and the Fishery Management Areas (FMAs) where bottom fishing occurs (in defined sub-areas within the FMAs, referred to Bottom Trawl, Midwater Trawl and Bottom Line Management Areas, with the exception of the Gascoyne Bottom and the Capel Bank Line Management Areas). FMAs are labelled as: 1) South Tasman Rise (this FMA has been closed to all demersal fishing since 2007, see Fig. S1), 2) Westpac Bank, 3) Northwest Challenger, 4) Central Lord Howe Rise, 5) North Lord Howe Rise, 6) West Norfolk, 7) Three Kings, 8) North Louisville, 9) Central Louisville, 10) South Louisville. Individual figures for each FMA and nested Bottom Trawl, Midwater Trawl and Bottom Line Management Areas are provided in the Supplementary Materials (Figs. S1-S10), along the Gascoyne and Capel Bank Bottom Line Management Areas (Fig. S11).

consistently implemented across Members engaging in midwater (targeting bentho-pelagic species) and bottom trawling (Geange *et al*., 2020; Penney, 2014; Rowden *et al*., 2025). No bottom fishing (other than exploratory fisheries which are covered under other SPRFMO CMMs) is allowed outside of the Fishery Management Areas (FMAs), except for standalone Bottom Line Management Areas “Capel Bank” and “Gascoyne” (Fig. S11), which do not have an assigned FMA.

Since 2019, CMM03 has been regularly updated to reflect best available information (SPRFMO, 2025a), including the development of the recently adopted Encounter Review Standard (ERS), the first such standard among deep-sea RFMOs (SPRFMO, 2024). The ERS describes Member or Cooperating Non-Contracting Party (CNCP) and Scientific Committee responsibilities when reviewing encounters with potential VMEs, which occur when bycatch of VME indicator taxa (*e.g.*, stony corals) in any trawl tow exceed predefined encounter thresholds, resulting in temporary suspension of fishing in the encounter area. Both the BFIAS and the ERS are periodically updated through a participatory process to reflect best practice, alignment with the Deep-Sea Fisheries Guidelines, and account for the best available scientific information. In combination with the Data Standards (SPRFMO, 2025b), these Standards are at the core of an ecosystem approach to deep-sea fisheries management in the SPRFMO Convention Area.

Standards can be fundamental to effective fisheries management, providing a structured and scientifically grounded basis for decision-making. Standards enable consistent application of methodologies across jurisdictions, facilitate the collection and exchange of comparable data, and support transparent evaluation of management outcomes (Anderson *et al*., 2015; Kirby and Ward, 2014). By incorporating best available science, standards help assess ecological risks, guide sustainable exploitation of marine resources, and ensure the protection of vulnerable marine ecosystems (Ardron *et al*., 2014; Cooke *et al*., 2023). Moreover, standards underpin adaptive management by allowing for systematic updates in response to emerging evidence and changing environmental conditions, thereby enhancing the resilience and accountability of fisheries governance frameworks (Free *et al*., 2020).

Here, we detail the structure and function of the BFIAS and ERS, their periodic updates to reflect best practice and scientific knowledge, and their role in operationalising an ecosystem approach to fisheries management. We also discuss gaps, uncertainties, and potential future improvements for these standards, including the better integration of cumulative impacts (such as climate change and cross-sectoral pressures), and discuss the need for universal impact assessment frameworks for RFMOs. Through the examples from SPRFMO, we illustrate the importance and role standards can play in achieving sustainable, science-based management of deep-sea fisheries in areas beyond national jurisdiction.

Bottom Fishery Impact Assessment Standard

The first BFIAS was adopted prior to the formalisation of SPRFMO in 2012, and since then, SPRFMO has progressively developed and implemented a fully formed package of CMMs which are key to achieving the objectives set in the Convention. Prior to the adoption of the BFIAS, bottom fishing impact assessments undertaken by Australia and New Zealand generally met the requirement to consider the impacts of fishing on VMEs, despite limited data on their distribution. However, the assessments did not adequately address the impacts on deep-sea target fish stocks (*e.g.*, Williams, 2011; SPRFMO, 2008). Both Members focussed their analysis of potential impacts on VMEs on the spatial footprint of fishing activities in relation to the likely distribution of VMEs to make inferences about the likelihood of SAIs on VMEs. Most importantly, the assessments failed to consider cumulative impacts from the combined effort footprints and/or catches of the two Members together as well as those impacts caused by other parties that had engaged in deep-sea fisheries in the past. Furthermore, several components of the initial BFIAS were subsequently superseded by the implementation of multiple CMMs, rendering them redundant.

In response to these issues, Australia and New Zealand agreed to review the initial BFIAS, recognising that it did not fully meet the key requirement of implementing an ecosystem approach, as mandated by the SPRFMO Convention. Assessing bottom fishing impacts on non-targeted fish species (quantification of discards) and non-fish species such as seabirds, marine mammals and reptiles was one of the key additions to help fill the ecosystem approach gap (Georgeson *et al*., 2018). An intersessional working group formed by the Members of Australia, New Zealand, the EU, the US, the SPRFMO Secretariat and the New Zealand High Seas Fishing Group (a body representing fishing industry interests) supported a comprehensive review of the BFIAS (Georgeson and Cryer, 2019). As a result, the BFIAS (SPRFMO, 2019a), was re-structured around the following key components: a) description of fishing activities, b) mapping and description of fishing areas and c) a risk and impact assessment framework. While the description of fishing activities and areas did not substantially change, the inclusion of an assessment framework was key to align the BFIAS with an ecosystem approach as required by the overarching SPRFMO Convention.

Risk and impact assessment framework

To support an ecosystem approach to fisheries management, the risk and impact assessment framework contained in the BFIAS is based on the methodology of Hobday *et al*. (2011) (Fig. 2). The first step of the framework includes defining the objectives, which are set in the SPRFMO Convention (SPRFMO, 2022):

> "*…through the application of the precautionary approach and an ecosystem approach to fisheries management, to ensure the long-term conservation and sustainable use of fishery resources and, in so doing, to safeguard the marine ecosystems in which these resources occur*."

The first step also includes identifying the assets (*e.g.*, target species and other ecosystem components) and the hazards these may face (*e.g.*, the fishing activity). The second step is the identification and assessment of risks, based on the previously identified assets and hazards. The third step is the identification of monitoring and mitigation measures, which should be iteratively evaluated to assess their performance. The framework is iterative and adaptive in that risks and impacts are periodically reassessed (hierarchically; individually and in combination) and management and monitoring plans are updated accordingly (Fig. 2).

Revision of the BFIAS is currently scheduled to occur at least every five years (earlier if needed), and this typically involves at least one Member that engages in bottom fisheries (*e.g.*, New Zealand) to run a participatory process with other Members who may have interests in bottom fisheries, independent scientists, fishing industry representatives, and environmental organisations. This type of approach, which is used by some Members in the management of fisheries within their national jurisdictions (McCay and Jentoft, 1996), allows for the identification of potential improvements from diverse perspectives. These suggestions are then reconciled by the leading Member and further presented to the SPRFMO Scientific Committee for consideration. Finally, the Scientific Committee provides advice to the SPRFMO Commission, which may adopt the BFIAS revision along with other scientific recommendations tabled by the Scientific Committee for that year.

Risk assessment for target species

Risk assessments for target fisheries species within the SPRFMO framework are undertaken following a structured, science-based process designed to evaluate the cumulative impacts of bottom fishing activities on principal target stocks, such as orange roughy (*Hoplostethus atlanticus*) and other target deep-sea species. The initial phase involves compiling detailed

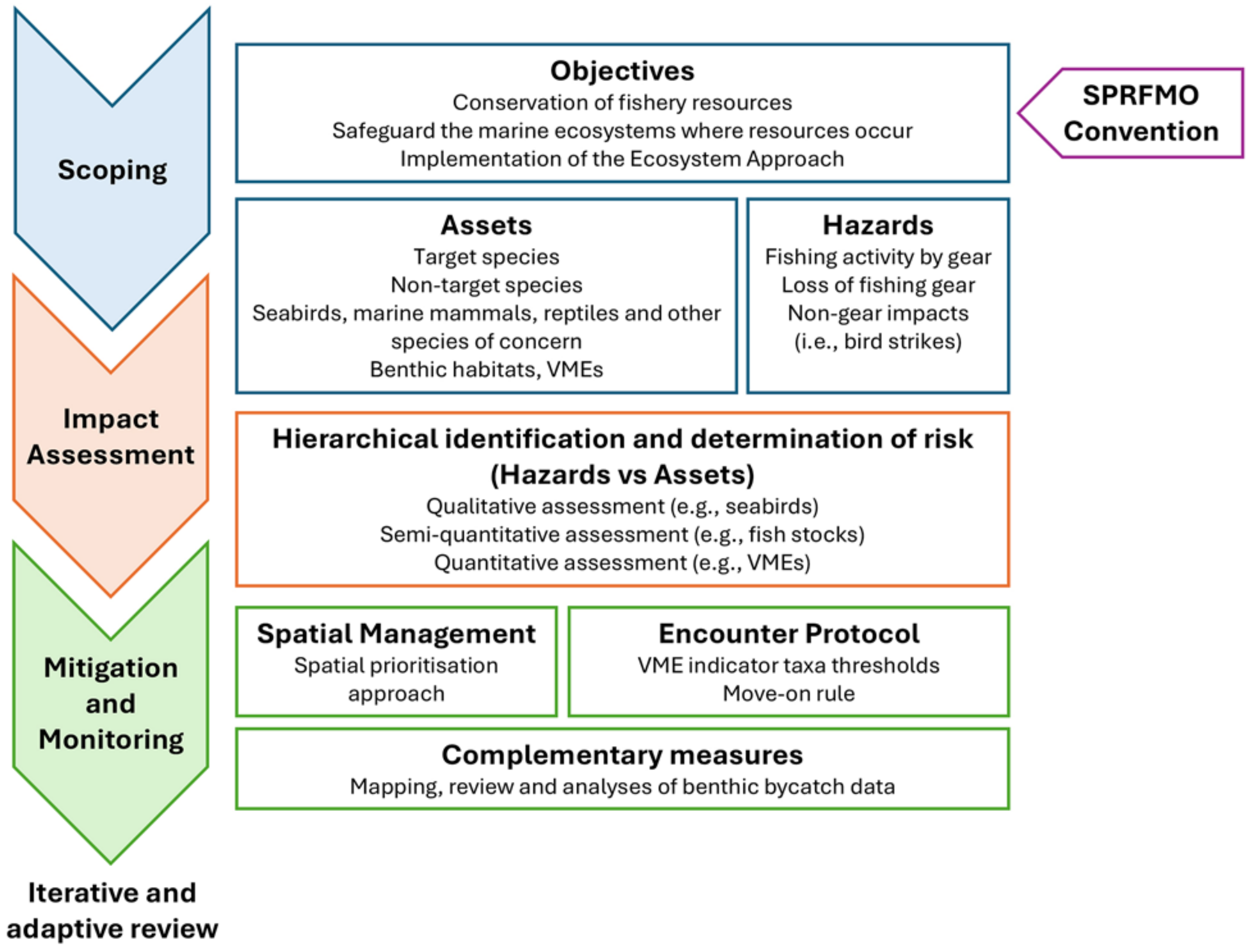


Fig. 2. Diagram depicting the main components of the risk and impact assessment framework provided by the BFIAS (SPRFMO, 2019). Mitigation and monitoring measures herein relate to impacts on VMEs.

catch and effort datasets, encompassing both spatial and temporal distributions of fishing activities. These data inform assessments of the current status of target populations. Biological parameters—including growth rates, longevity, productivity, and stock structure—are incorporated to evaluate the resilience and vulnerability of these populations to fishing pressure.

The assessment approach combines both qualitative and quantitative methodologies, including formal stock assessments, biomass indices, and the establishment of reference points to guide sustainable exploitation. In circumstances where data are limited, the application of precautionary principles is emphasised, with uncertainties explicitly recognised throughout the process. The assessment of cumulative impacts accounts for fishing activities across multiple fleets and jurisdictions, ensuring that management decisions are underpinned by the best available science and reflect the ecosystem approach mandated by the SPRFMO Convention. This risk assessment process is adaptive, with periodic updates in response to new data and scientific advancements and is subject to review by the SPRFMO Scientific Committee to ensure transparency and accountability.

Risk assessment for marine mammals, seabirds, reptiles and other species of concern

Risk assessments for non-target species—including marine mammals, seabirds, reptiles, and other species of concern—within the SPRFMO framework are undertaken using a structured blend of qualitative and quantitative methodologies. The process is initiated with the identification of potentially impacted species, utilising observer data, bycatch records, and available species distribution information. For each taxonomic group, assessments consider the likelihood of interaction with fishing gear, the frequency and severity of observed bycatch events, and biological characteristics influencing vulnerability, such as population size, reproductive capacity, and migratory behaviour.

Where sufficient data are available, formal ecological risk assessment tools—such as Productivity-Susceptibility

Analysis (PSA) (Hobday *et al*., 2007, 2011) or Sustainability Assessment for Fishing Effects (SAFE) (Zhou and Griffiths, 2008)—are employed to evaluate the relative risks faced by different species. For example, a SAFE assessment for teleost and chondrichthyan species in the SPRFMO Convention Area was completed in 2025 (Keller *et al*., 2025). The SAFE methodology derives a proxy for fishing mortality based on four susceptibility components (availability of the species to the fishing fleet, encounterability of the gear given the species' vertical distribution, gear selectivity, and post-capture survival) and compares this to F-based (sustainability) reference points (*e.g.* F_{msy}, F_{lim}, and F_{crash}) derived from basic life-history parameters. Keller *et al*. (2025) concluded that from all the assessed taxa, deepwater sharks are the taxonomic group at the highest risk for bottom fishing and the SPRFMO Scientific Committee has recommended several management measures to mitigate this risk (SPRFMO, 2025c).

In instances where data are limited, expert judgement and precautionary principles are applied, with uncertainties explicitly acknowledged. The assessment of cumulative impacts integrates information across fleets and years, ensuring that management measures address both direct and indirect effects of fishing activities. Outcomes from these assessments inform the development and refinement of mitigation measures, including gear modifications, spatial closures, and reporting requirements, which are subsequently reviewed by the SPRFMO Scientific Committee. This process ensures that management actions are evidence-based, transparent, and consistent with the broader ecosystem approach mandated by the SPRFMO Convention.

Risk assessment for benthic habitats and VMEs

When assessing risks to benthic habitats and VMEs under the BFIAS, criteria such as bottom fishing intensity, duration, spatial extent, and cumulative impacts are systematically evaluated. In combination, these factors provide a comprehensive assessment of the overall risk posed by fishing activities to benthic environments and VMEs. The BFIAS provides examples of qualitative and quantitative methodologies to help assess risks and impacts of bottom fishing on VMEs, with the most recent iteration of the Bottom Fishery Impact Assessment (BFIA) for New Zealand and Australian bottom fisheries (Anderson *et al*., 2024) including a benthic quantitative impact assessment based on the dynamic relative benthic status (dRBS), a fully quantitative methodology to estimate the benthic status of a species, species group, or habitat (Pitcher *et al*., 2017). The dRBS as applied in the BFIA makes use of historical fishing effort annual data (as swept area ratio; SAR), habitat suitability data layers for VME indicator taxa (transformed to better reflect the presence of a VME, and account for model uncertainty) (Stephenson *et al*., 2021), and VME indicator taxon-specific depletion and recovery rates (Anderson *et al*., 2024). The BFIAS indicates that benthic impact assessments should be conducted at spatial scales that are ecologically relevant; however, it acknowledges that data limitations may necessitate the use of alternative spatial units, such as undersea features or management areas. The current focus of the application of the dRBS status assessment is for Fishery Management Areas (FMAs), which include areas open (Bottom Trawl, Midwater trawl and Bottom Line Management Areas) and closed (the remainder of the FMA) to bottom fishing. Estimates of the dRBS for each assessed VME indicator taxon are used to determine whether predicted suitable habitats in FMAs are adequately protected from SAIs. Consistent with the Marine Stewardship Standard (MSC, 2024), dRBS values averaged over the FMA below 80% are interpreted "*as reductions in habitat structure and function below 80% of the unimpacted state*" that signal "*serious or irreversible harm*" (*i.e.*, SAIs) for these "*more sensitive*" habitats, such as VMEs. This approach therefore assumes that a certain level of impact (due to fishing) can be compatible with avoiding SAIs on VMEs. It is important to note that such thresholds are inherently scale-dependent, and their interpretation may vary with the spatial resolution of the assessment.

Mitigation, management and monitoring measures

Under CMM03, most of the SPRFMO Convention Area remains closed to bottom fishing (excluding exploratory fisheries), with the exception of designated FMAs that allow bottom long lining, bottom trawling and midwater trawling (targeting bentho-pelagic species such as alfonsinos) within clearly defined boundaries (with the exception of the Capel Bank and the Gascoyne Bottom Line Management Areas, see Fig. S11) (Table 1). This spatial management approach was designed to ensure that a large percentage of the model-predicted suitable habitat for VME indicator taxa remains outside areas open to bottom fishing, thereby providing for the long-term conservation and sustainable use of deep-sea fishery resources. The design of this measure aims to provide an assurance that bottom fishing would not have SAIs on VMEs, considering the spatial extent of the impact of fishing activities relative to the availability of predicted habitat for VME indicator taxa within the broader SPRFMO area. As of 2026, approximately 12.2% and 12.7% of the SPRFMO Convention Area within fishable depths remain open to bottom and midwater trawling, respectively (Table 1).

To account for the residual risk associated with the spatial management approach (see subheading - Key gaps and uncertainties), a VME encounter protocol was established as the main complementary management measure. The protocol includes the temporary closure of an area if specified weights of VME indicator taxa are exceeded in a trawl. This protocol provides a

Table 1. Size (area in km^2) of the entire SPRFMO Convention Area and its overlap with fishable depths (approximately to a 1 400m depth), and percentage of area open to bottom fishing (broken down by gear).

Zone	Area (km^2)	% Open to bottom trawling	% Open to midwater trawl	% Open to bottom long line
Convention Area	59 118 289	0.108	0.111	0.201
Convention Area (0–1 400m depth)	349 320	12.178	12.735	25.454

mechanism for the rapid curtailment of bottom fishing in an area where the bycatch of VME indicator taxa is unexpectedly high relative to taxon-specific cumulative distributions of historical VME indicator taxa bycatch from within the SPRFMO Convention Area (> than the 99th percentile of historic catches) (Geange *et al.*, 2020; Rowden *et al.*, 2025). Following the triggering of an encounter, the encounter is reviewed by the Member state and then by the Scientific Committee following the requirements provided by the Encounter Review Standard (see heading - Encounter Review Standard), with appropriate management recommendations put forward to the SPRFMO Commission. The BFIAS mandates the reporting of these existing management measures, and the inclusion of other complementary monitoring measures (such as fine-resolution mapping of benthic bycatch; Tablada *et al.*, 2022; 2023), providing for a continuous evaluation based on best available information.

Key gaps and uncertainties

The BFIAS requires that uncertainties within the risk and impact assessment framework be explicitly stated. This statement includes identifying areas where future research or additional data collection may be necessary to reduce or resolve these uncertainties. Current uncertainties for key fish stock assessments include poor knowledge of the stock structure for target species (*i.e.*, orange roughy), gaps in key biological information (growth, longevity, productivity) and indices of biomass and/or fishing mortality for key target stocks and SPRFMO-specific management targets and limits for key targets and other stocks. Due to the inherently low productivity of deep-sea fisheries and the life history traits of the main target species such as orange roughy, as well as the characteristics of the ecosystems that support them, significant ecological changes in these systems are likely to develop, and recover, over much longer timescales compared with more productive shallower systems. As a result, the full extent of the impacts from existing orange roughy fisheries in the high seas of the South Pacific may not yet be fully apparent and, therefore, inherently hard to estimate (Tingley and Dunn, 2018). Uncertainties in the assessment of impacts on marine mammals, seabirds, reptiles and other species of concern arise from several sources, including inaccurate identification of caught specimens by fishers and observers, limited knowledge of the distribution of certain at-risk species, and insufficient estimates of population size and productivity for species with broad ranges and/or poorly understood biology. As an example, the most recent SAFE assessment for teleost and chondrichthyan species (Keller *et al*., 2025) highlighted the lack of information about the distribution of these species in the SPRFMO Convention Area (and significant divergences between the different data sources) and the biological productivity attributes of some of the species assessed. For deep sea chondrichthyans, inaccurate species identification remains an issue.

Regarding assessment of benthic habitats and VMEs, a considerable degree of uncertainty is associated with the modelling of the habitat suitability of VME indicator taxa across the western part of the SPRFMO Convention Area (Stephenson *et al*., 2021). These models underpin the quantitative assessment of benthic impacts due to the impracticality of undertaking benthic surveys across such a large, deep and remote area. Recognising the limitations of habitat suitability index models, especially those based on presence-only data (Stephenson *et al*., 2021), recent efforts have focused on the development of abundance models for VME indicator taxa (Bennion *et al*., 2025a), which are based on observation data from sampled areas (seafloor video imagery) and represent an important step forward given the current lack of understanding between abundance and predictions of suitable habitat. However, data paucity regarding distribution of benthic taxa remains the biggest hurdle, with most of the survey data used in modelling efforts collected in areas adjacent to the western part of the SPRFMO Convention Area, mainly New Zealand's Exclusive Economic Zone (EEZ) (Bennion *et al*., 2024, 2025a).

Future improvements

Despite the BFIAS having performed relatively well against an independent evaluation of impact assessments across deep-sea fisheries RFMOs (DOSI, 2022; Kaikkonen *et al*., 2024), it can be improved in many respects. The most recent review of the BFIAS led by New Zealand acknowledges missing components to further progress the ecosystem approach to fisheries management, such as estimation of impacts across ecosystem levels (*e.g.*, through trophic modelling) and missing linkages between the assessed components of the ecosystem (Arkhipkin and Tablada, 2025). To be able to include and meaningfully inform such changes to the BFIAS, efforts must be made to collect more environmental and ecological data that would allow, among other things, improved environmental baseline information and better mapping and identification of VMEs and other important benthic habitats (DOSI, 2022; Kaikkonen *et al*., 2024). VME indicator taxa such as corals and sponges can form significant habitats known to support a variety of biodiversity, including commercially important fish species (De Clippele *et al*., 2025) and fulfil ecosystem functions such as bentho-pelagic coupling and nutrient and carbon cycling (*e.g.*, Maier at al., 2020; De Clippele *et al*., 2021). The limited availability of data on the composition and size structure of communities dominated by VME indicator taxa make it difficult to quantify their functional attributes. While ecosystem functions provided by VMEs are influenced by factors such as spatial extent, body size and age structure, accurately determining these effects requires abundance data collected at fine spatial scales (Susini *et al*., 2025; Vad *et al*., 2025).

The BFIAS provides for the use of alternative sources of information to direct observations from the seafloor to identify areas known or likely to support VMEs. These sources include benthic bycatch records, predictive models for VME indicator taxa and known distribution of underwater topographic features (particularly seamounts) that may support VME indicator taxa (*i.e.*, Clark *et al*., 2022). However, the BFIAS does not provide a multi-criteria framework for integrating these diverse sources of information (including data collected by seabed biodiversity surveys) to support identification of VMEs (Morato *et al*., 2018). Although data collected directly from areas of interest is generally considered the best way to map areas likely to host VMEs, there is currently no consensus among experts on how to identify VMEs using imagery data (although progress towards developing a consensus is being made; see Baco *et al*., 2023). Furthermore, the operational and logistical costs associated with such direct surveys are extremely high. The BFIAS would benefit from including a reference to a robust methodology to cost-effectively identify or estimate VMEs (Bennion *et al*., 2025a; Stephenson *et al*., 2025), which could subsequently be used to support an assessment of the likelihood of SAIs on VMEs due to fishing impacts. The Deep-Sea Fisheries Guidelines provide guidance for identifying VMEs and assessing SAIs; however, they offer limited practical direction for evaluating and operationalising what constitutes a SAI in practice (Rowden *et al*., 2024). An important management part of this gap is the absence of a pragmatic and practical threshold that can help differentiate between an acceptable and unacceptable impacted state (Hiddink *et al*., 2023). Without defined ecologically relevant thresholds to distinguish what constitutes a SAI, and without a systematic process for identifying areas that qualify as VMEs, the BFIAS is currently unable to fully operationalise the requirements of multiple UNGA Resolutions that call for the prevention of SAIs on VMEs in the high seas.

While the BFIAS provides for consideration of cumulative impacts from fishing, it currently does not require the inclusion of other impacts such as those derived from climate change resulting from increased water temperatures, ocean acidification and deoxygenation, or any other human activities other than fishing. The lack of this requirement is significant given the SPRFMO Convention's focus on an ecosystem-based approach to fisheries management. Climate change is already having impacts on marine ecosystems, which in the future may be exacerbated, including on water column productivity, on habitats of importance to commercial fish species and on fisheries (Pinkerton, 2017; Datta *et al*., 2024). Therefore, these other actual or potential impacts should be assessed as cumulative impacts alongside present and historical fishing activity (FAO, 2019). Although information on how climate change affects deep-sea communities remains limited, environmental shifts driven by climate change will increase uncertainty in assessing the impacts of bottom fishing, adding another degree of complexity to risk assessment and related management decisions (Cummings *et al*., 2021; Pentz, 2018). The exclusion of non-fishing impacts from the BFIAS reflects the current limited understanding of benthic ecosystems within areas open to bottom fishing in the SPRFMO Convention Area, rather a deliberate omission, noting that RFMOs are mandated to adopt rules for managing fisheries exclusively. For other RFMO areas, information about impacts from non-fishing activities may be available and can be included directly in impact assessments. For example, NAFO has started exploring the inclusion of impacts such as oil spills, noise and seabed litter (Durán Muñoz *et al*., 2022). In the South Pacific there are ongoing research efforts aimed at addressing the knowledge gaps around assessing cumulative impacts (*e.g.*, Gammon *et al*., 2018; Hitt *et al*., 2020; Tracey *et al*., 2024). Of particular relevance is the recent work exploring the implications for the management of deep-sea corals facing multiple human-driven impacts within New Zealand's national waters (Stephenson *et al*., 2023), which could be applied to the western part of the SPRFMO Convention Area. Characterising climate-driven changes in taxa occurrence, abundance and distributions is fundamental to any climate change strategy. In the context of SPRFMO bottom fisheries, key taxa include VME indicator taxa, vulnerable non-target species (*e.g.*, deep-water sharks, rays and chimaeras) and commercially valuable species. Extensive work undertaken by New Zealand within its jurisdictional waters has modelled the future distribution of suitable habitat for deep-water corals and demersal fish species, including orange roughy, under projected seafloor environmental conditions (Anderson *et al*., 2022; Brough *et al*., 2025) using climate models tailored to the South Pacific (Behrens *et al*., 2020). These approaches could be extended to the western part of SPRFMO Convention Area, where most of bottom fishing occurs, and incorporated into the BFIA to assess likely shifts in future fishing effort. This would enable forward looking risk assessments that account for future spatial overlap between fisheries species of interest and fisheries, identify potential climate refugia for VME indicator taxa, and support initial evaluation of cumulative impacts, including those arising by cross-sectoral activities (Judah *et al*., 2025; Zelli *et al*., 2025). Climate change vulnerability assessments (*e.g.*, Cerutti-Pereyra *et al*. 2024), which use species' life history traits to assess their capacity to persist under future environmental conditions, could also be adapted to the SPRFMO Convention Area and incorporated into future iterations of the BFIA, complementing existing risk assessments for chondrichthyans and other vulnerable taxa (*e.g.*, Keller *et al*. (2025), <u>see subheading - Risk assessment for marine mammals, seabirds, reptiles and other species of concern).</u>

Encounter Review Standard

As already noted above, SPRFMO operates a VME encounter protocol as a complementary management measure to the spatial management which is the primary means by which SAIs to VMEs are prevented. As such, this standard is important for supporting the overall management measures that are put in place to implement an ecosystem approach to fisheries management. Specifically, CMM03 requires that "*where VME indicator taxa are encountered in any one tow at or above the weight threshold in Annex 6A, or three or more different VME indicator taxa at or above the weight thresholds in Annex 6B, Members and CNCPs shall require any vessel flying their flag to cease bottom fishing immediately within an encounter area of one (1) nautical mile either side of the trawl track extended by one (1) nautical mile at each end*" (hereafter referred to as the encounter area). Vessels are then required to report the encounter immediately to the Member or CNCP whose flag the vessel is flying and to the Secretariat, in accordance with the Guidelines for the preparation and submission of notifications of encounters with potential VMEs, contained in Annex 7 of CMM03.

Since the implementation of the encounter protocol in 2019, SPRFMO has progressively developed guidance to assess encounters with potential VMEs, which has been consolidated in the Encounter Review Standard (ERS). The ERS aligns with the Deep-sea Fisheries Guidelines, considers biologically relevant scales for assessing SAIs on VMEs (*i.e.*, bioregions, see Bennion *et al*., 2025b), and provides a streamlined, time-efficient method that accommodates the different capacities of Member States to participate and undertake encounter reviews. New Zealand developed the ERS based on existing materials (Milardi and Geange, 2021) through a participatory process that included representatives from both fishing industry and environmental organisations. The ERS is structured around the steps that the Member (or CNCP) and the Scientific Committee must follow after an encounter has been notified (Fig. 3).

Ultimately, the outcome of the application of the ERS is to provide advice to the SPRFMO Commission, which then can determine appropriate management actions for each encounter to prevent SAIs on VMEs, which may include: the closing of areas to some or all bottom fishing gear; temporal restrictions; spatial restrictions; and reopening areas.

Member review

Encounter detailed description

A Member needs to provide a detailed description of each encounter for the consideration by the Scientific Committee. This description should contain date and location, gear and vessel specifications, a detailed composition of the benthic bycatch associated to the encounter, including a characterisation of the ecology and biology of each VME indicator taxon encountered and the best available information related to its catchability (Stephenson *et al*., 2022). Location of historical bottom trawl tows (and associated benthic bycatch data) within the encounter area (and surrounding areas, ideally up to the entire Bottom Trawl Management Area within which the encounter took place) as well as spatial predictions of VME indicator taxa (habitat suitability index models, abundance models) need to be provided as well. Information regarding the oceanography, topography and geomorphology for the area of interest, where available, must be included. The ERS provides technical requirements for figures (maps) that the Member may develop to include some of these data and allows for the data confidentiality considerations. Where data is subject to internal regulations regarding the protection of private and commercially sensitive information, the Member can choose to either establish a formal data confidentiality agreement with the Scientific Committee or to withhold the data (while providing a clear description of the nature of the data being withheld along with its limitations).

VME assessment

The ERS does not provide a formalised mechanism to assess whether a VME is known or likely to occur within the encounter area but allows Members to use two complementary approaches. The first is a direct assessment, based on data collected from the encounter area (*i.e.*, seafloor imagery), and the second is an indirect assessment, based on best available information collated by the Member. While the ERS acknowledges that the direct assessment method is likely to provide the most robust information for identifying VMEs and should be preferred, evidence from a direct assessment can be further strengthened by integrating information from indirect assessments (Baco *et al*., 2023). However, there are often challenges related to the spatial scale of surveys and the

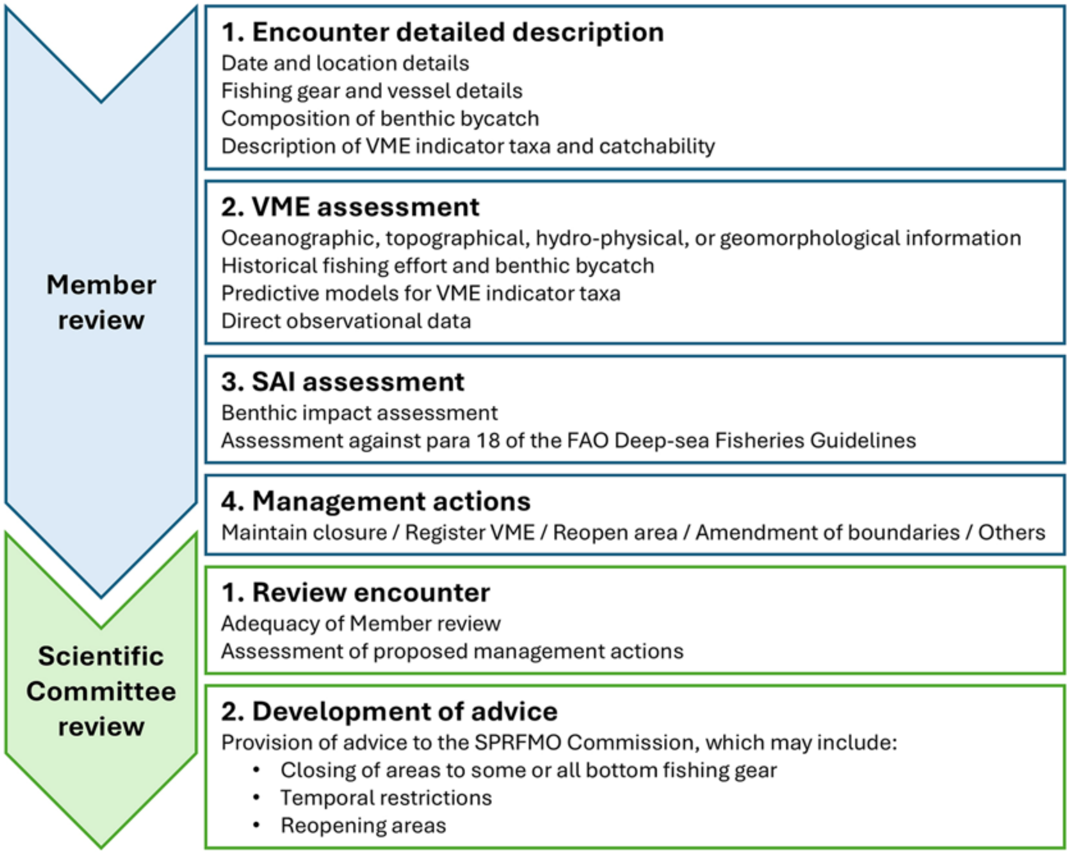


Fig. 3. Diagram depicting the main steps for both the Member and the Scientific Committee as outlined in the Encounter Review Standard (SPRFMO, 2024).

resourcing required to undertake surveys of areas likely to host VMEs, and only a very limited number of sites within the western part of the SPRFMO Convention Area have been surveyed in the past (Clark *et al*., 2015; Clark and Roberts, 2008).

The ERS also supports the use of multi-criteria analysis methods as a robust approach for evaluating different "lines of evidence" and the "weight" of these lines of evidence against sections of the Deep-Sea Fisheries Guidelines and determining whether an encounter constitutes evidence of a VME. Such a multi-criteria approach for assessments is widely used in environmental decision-making processes (*e.g.*, Turschwell *et al*., 2023, Vanegas-Cantarero *et al*., 2022) and is included in the Northwest Atlantic Fisheries Organization (NAFO) and International Council for the Exploration of the Sea (ICES) 'benchmark' processes for identifying VMEs and assessing SAIs (NAFO, 2020; ICES, 2022). Multi-criteria assessments following the ERS should integrate as much relevant information as possible into the process of identifying the known or likely occurrence of a VME. This assessment includes a variety of data sources, from direct observational methods such as video, echo-sounder and multi-beam surveys, to indirect methods such as evaluation of historical benthic bycatch, thresholding of predictive modelling for VME indicator taxa distribution, and assessment of the presence of topographical, hydro-physical or geomorphological features which may support VMEs. Other RFMOs have opted to start the process to formalise similar multi-criteria approaches to the one provided in the ERS to identify VMEs (*e.g.*, Curtis *et al*., 2020; Kenny *et al*., 2025; Warawa *et al*., 2025), but due to a lack of an explicit framework in SPRFMO to identify VMEs, the ERS currently provides flexibility to Members undertaking encounter reviews.

SAI assessment

The ERS requires an evaluation of whether reopening the encounter area will expose any VMEs to SAIs, noting that the range of relevant ecological spatial scales at which VMEs can be identified remains an open question. That determination should be made on a case-by-case basis through the application of relevant provisions in the Deep-sea Fisheries Guidelines, particularly Section 3.3 and Article 47. Like the multi-criteria approach in the VME assessment, the ERS provides flexibility to how Members can assess likelihood of SAIs on VMEs (if VMEs are deemed to be, or likely to be, in the encounter area). In the ERS, a minimum of an "expert judgement" approach is provided for, although semi-quantitative and fully quantitative impact assessment methods are recommended, subject to data availability and Member's capacity (Peixoto *et al*., 2025; Pitcher *et al*., 2017).

Management actions

The ERS requires Members undertaking encounter reviews to identify management actions they consider necessary to prevent SAIs on VMEs based on the results of their application of the ERS. The ERS offers a variety of actions Members can choose from (*i.e.*, maintaining a closure, re-opening an area) but also offers flexibility to allow Members to suggest other actions that may be deemed appropriate to the specific context of an encounter.

As of October 2025, the ERS has been put into practice once since its formal adoption, with New Zealand providing a review based on an indirect approach that makes use of the best available information, including information on the geomorphology and biogeography of the encounter area, historical VME indicator taxa bycatch data, habitat suitability index models and abundance models for VME indicator taxa, historical benthic invertebrates records and a quantitative benthic impact assessment using the dRBS approach (New Zealand, 2025).

Scientific Committee review

At its annual meeting, the SPRFMO Scientific Committee must review all encounter reviews tabled by Members or CNCPs. In reviewing the assessments provided by Members, for each encounter, the Scientific Committee is required to consider the detailed analyses while applying the Deep-sea Fisheries Guidelines, and to determine the adequacy of the review, including the suggested management actions. The ERS suggests that the Scientific Committee develops management actions and advice to the SPRFMO Commission based on the Member's recommendations but provides flexibility in allowing the Scientific Committee to determine any action or advice it may consider appropriate for each encounter area and, as appropriate, all encounter areas combined. Ultimately, final decisions on management actions for each encounter are decided by the SPRFMO Commission.

Key gaps and uncertainties

Like the BFIAS, the ERS requires Members to explicitly refer to known limitations and uncertainties of their analysis, including how these are reflected in their suggested management actions. The ERS acknowledges that almost every source of information regarding the identification and location of VMEs in the South Pacific high seas, as well as the definition of what constitutes a SAI, is embedded in a significant degree of uncertainty. For example, with respect to identifying VMEs, there is a lack of specific understanding about the trawl catchability of VME indicator taxa, which is likely to be variable across the SPRFMO Convention Area depending on the geomorphological attributes of each area and be taxon-specific (Rowden *et al*., 2024; Stephenson *et al*., 2022). Using historical fishing effort and benthic bycatch data carries other limitations other than catchability of VME indicator taxa, such as limited geolocation accuracy, particularly for the early years of the orange roughy fisheries in the high seas, when no specific regulatory measures and associated data reporting standards were in place (Tingley and Dunn, 2018). Modelled predictions of the distribution of VME indicator taxa are constrained by coarse-level taxonomic data, integration of data from multiple sources and multiple points in time (*e.g.*, fisheries bycatch, research surveys), limited coverage of data across geographical and environmental spaces, which combined are impeding the development of highly-accurate, fine-scale, species-specific predictions (Stephenson *et al*., 2021).

Despite the assumed uncertainties, the ERS requires consideration of the Deep-sea Fisheries Guidelines and the precautionary approach, meaning that not being in possession of highly certain and accurate information regarding location and extent of VMEs is not an impediment to implementing management actions (van Denderen *et al*., 2023).

Future improvements

The relationship between the biomass of benthic bycatch recorded on the surface and the biomass on the seafloor is poorly understood. Generally, bottom trawl gear is relatively inefficient at catching benthic invertebrates, including VME indicator taxa, so the amount of bycatch material landed on deck is unlikely to represent the scale of impact on the seafloor because some of the catch may be broken into small fragments and lost from the net before it is recovered to the surface for further examination (Stephenson *et al*., 2022). In SPRFMO bottom fisheries, it has been acknowledged that existing data on the catch efficiency of trawl gears for VME indicator taxa is broadly consistent and indicates that catchabilities are generally very low, meaning only a small fraction of VME indicator taxa on the seafloor are caught and retained by demersal fish trawls (Geange *et al*., 2019; Stephenson *et al*., 2022). Lack of data from the SPRFMO fishing grounds is a known impediment for determining density/biomass estimates of VME indicator taxa and the development of area-based and taxon-specific catchability estimates, both of which are ideally important inputs for determining thresholds for the VME encounter protocol and the ERS. To date, a pragmatic but data-informed approach has been used to develop candidate threshold weights (Geange *et al*., 2020), and the possibility of a research programme to allow the determination of more robust taxon-specific estimates of catchability has been explored (Stephenson *et al*., 2022), although its cost has been deemed too high and its benefits uncertain. The

North Pacific Fisheries Commission (NPFC) has recently undertaken work (Rooper *et al*., 2025) that builds on the approach adopted by SPRFMO and outlined in Geange *et al*. (2020). Subject to the availability of suitable data from within the SPRFMO Convention Area or adjacent fishing grounds (*e.g.*, parts of the New Zealand's EEZ), the approach developed by Rooper *et al*. (2025) could be trialled for a certain subset of VME indicator taxa. More robust thresholds would likely improve determination of likelihood of SAI on a VME and enhance the overall applicability of the ERS. While it is widely accepted that encounter thresholds should be data-informed and scientifically-driven, RFMO-specific bottom fisheries management considerations, such as spatial management arrangements, gear-specific restrictions, levels of observer coverage and move-on distances, may also inform the setting of thresholds (Reid, 2023). As of 2026, SPRFMO is the only deep-sea RFMO that has used context-specific bycatch data to develop a distinct set of threshold weights for VME indicator taxa designed to inform the biodiversity component of the encounter protocol. This component is triggered when the bycatch weight of at least three VME indicator taxa in one given tow reach or exceed the values set in Annex 6B of CMM03, as an indication that diverse seabed fauna may represent the presence of a VME (Watling and Auster, 2021).

Other potential improvements that have been identified but not addressed yet refer to the application of the dRBS, which is relevant to the BFIAS and the ERS, to determine likelihood of SAIs on VMEs. The lack of status thresholds to determine if a SAI on a VME has occurred (or likely occurred), and at which spatial scales these thresholds can be applied, are outstanding issues that remain to be addressed (Arkhipkin and Tablada, 2025). Progress is being made in the development of approaches to define SAIs quantitatively using the 'range of natural variation' approach (Hiddink *et al*., 2023). This approach defines a good state of an indicator, such as VME abundance or biomass, as an indicator value that falls within the long-term natural variation of that indicator in time-series from minimally impacted locations. Although very few time-series are likely to exist for VME indicator taxa, fitting general relationships between the threshold for good state and environmental (*e.g.* depth) and life-history (*e.g.* longevity) parameters is likely to allow the extrapolation of thresholds for VMEs in the SPRFMO Convention Area. These thresholds (relative to carrying capacity / long-term mean abundance in minimally impacted locations) are likely to be much higher for VME indicator taxa than those applicable to shallower water benthic communities (Hiddink *et al*., 2023).

Both the BFIAS and the ERS would benefit from having reference points in terms of relative benthic status and spatial scales that are of ecological relevance to VMEs, even more so if they were to be tailored for each VME indicator taxon.

While the ERS offers a degree of flexibility to accommodate each Member's capacity and resources to undertake encounter reviews, a comprehensive application of the ERS may require significant effort and time (New Zealand, 2025). All the possible enhancements to the ERS discussed above would likely result in efficiencies when reviewing potential encounters with VMEs. A more streamlined ERS would be desirable if SPRFMO bottom fisheries were to significantly expand (in terms of effort and/or spatially), as this could increase the number of encounters triggered in a fishing year.

Looking ahead

Detected deficiencies and limitations across the different RFMOs that require impact assessments of deep-sea fisheries on the ecosystem are due, at least in part, to elements and criteria that are missing from the Deep-sea Fisheries Guidelines (DOSI, 2022; Kaikkonen *et al*., 2024). Having a structured universal bottom fishing impact assessment standard could solve these deficiencies and allow for inter-comparability among RFMOs. Differences between RFMOs, such as data availability, scientific capacity, and the value of the fishery, should be considered, ensuring that a degree of flexibility is incorporated when designing such a standard. For example, data paucity on actual VMEs including connectivity, community composition and ecosystem function is the most critical impeding factor across RFMOs to provide appropriate baseline information in their respective benthic impact assessments (DOSI, 2022; Kaikkonen *et al*., 2024). While most RFMOs have opted to model predicted habitat suitability for VME indicator taxa as a proxy for VME occurrence (which misses the aforementioned aspects of connectivity, community composition and function), this is not evenly applied across RFMOs, due to the different RFMO-specific lists of VME indicator taxa (Baco *et al*., 2023). Some RFMOs have developed more comprehensive lists of VME indicator taxa than others (and often using different levels of taxonomic resolution), in part due to the topographic and morphological characteristics of each geographical area (Baco *et al*., 2023; Reid, 2023). Another critical difference to consider when designing an across-RFMO standard relates to fishery-independent surveys. While such surveys are routinely carried out in the NAFO Regulatory Area and the collected data is used in the multi-criteria approach designed to identify VMEs (Kenchington *et al*., 2026), other deep-sea RFMOs may not have the means to fund such surveys and lack the capacity to support such a time and data-consuming scientific process.

Recent independent reviews on the implementation of the ecosystem approach (Fletcher, 2020) and the Deep-sea Fisheries Guidelines (Thompson and Reid, 2024) by RFMOs have identified important achievements but also gaps. Specifically, Fletcher (2020) identified that the major gaps relate to ecological wellbeing (notably the lack of inclusion of climate change considerations, see subheading - Future improvements) and human wellbeing (missing economic and/or social aspects). Importantly, Fletcher (2020) noted that many of the assessed RFMOs engaging in deep-sea fisheries have tasked progressing the implementation of an ecosystem approach to a subsidiary scientific body (*e.g.*, SPRFMO Scientific Committee). However, the implementation of the ecosystem approach should be guided by an overarching strategy (FAO, 2012) and include long-term management plans with appropriate tracking and monitoring systems in place to assess progress, something that NAFO has begun to implement (Mariano Koen-Alonso *et al*., 2019) and, we believe, SPRFMO should consider. Fletcher *et al*. (2020) also noted that despite SPRFMO being one of the most recently established RFMOs, it has managed to consider half of the key components regarding implementation of an ecosystem approach to fisheries (FAO, 2012). Furthermore, it must be acknowledged that SPRFMO manages three fishery resources (jack mackerel, flying jumbo squid and orange roughy) that are ecologically and geographically distinct, and with a varying degree of involvement across membership, adding an extra layer of complexity and influencing the implementation of an ecosystem approach, which is variable across each fishery. In this regard, SPRFMO could consider diverse ways to implement an ecosystem approach based on the uniqueness of its fisheries, including the diverse requirements for assessments, capacity of engaged Members, availability of data and scientific knowledge and objectives (ICES, 2024).

Arguably the most comprehensive independent performance evaluation of RFMOs to date has identified that despite its recent establishment, SPRFMO (out of the 16 assessed RFMOs) ranked above average (Carmine *et al*., 2025). While Carmine *et al*. (2025) acknowledged the relative appropriateness of existing measures across SPRFMO managed fisheries (which by definition include the standards being discussed here, but also other aspects such as governance tools), this does not necessarily translate to achieving demonstrable results in terms of implementing the ecosystem approach (interpreted as management success). Significantly, none of the 16 assessed RFMOs reviewed by Carmine *et al*. (2025) achieved results deemed as best-practise, indicating that performance gaps are not unique but rather common, even among higher-performing RFMOs. Carmine *et al*. (2025) and similar publications understandably analyse RFMOs in their entirety and typically do not provide individual evaluations for each fishery, which may differ significantly.

Within the SPRFMO context of bottom fisheries, the BFIAS and the ERS acknowledge that there are important aspects that remain unresolved, including the lack of practical and operational definitions for VMEs and SAIs. However, many of these unresolved issues are common to other RFMOs and addressing them would improve the likelihood of generating universal standards for implementing ecosystem-based fisheries management in the high seas. For example, the spatial scales at which to identify, map, and assess impacts on VMEs (following the Deep-sea Fisheries Guidelines reference to "species groups, communities, habitats and features") need to be ecologically relevant. Providing clarity on SAIs and VMEs would have consequences for both the BFIAS and the ERS, as it could facilitate the development and adoption of operational thresholds to be included in quantitative assessments. The development and establishment of a data-driven, pragmatic approach to identify VMEs across the SPRFMO Convention Area would allow the population of the VME register (Annex 9 of CMM03), where locations of known VMEs within the SPRFMO Convention Area are listed, which as of 2026 remains empty. The empty register can be partly justified by the fact that, as already mentioned, SPRFMO relies on excluding a significant amount of the predicted suitable habitat for each VME indicator taxon within FMAs as a way to avoid SAIs on VMEs (SPRFMO, 2023), therefore postponing the issue of VME identification across large spatial scales (*e.g.*, FMAs) until availability of relevant data improves (Ardron *et al*., 2014). However, the application of the ERS may require undertaking identification of potential VMEs at relatively small spatial scales (*i.e.*, the area that results temporarily closed to fishing). These ad-hoc applications of the ERS may lead to the VME register being progressively populated, subject to the management outcomes of each assessed encounter as determined by the SPRFMO Commission.

The Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction (BBNJ Agreement) adopted in 2023 entered into force in January 2026. The BBNJ Agreement is likely to have consequences for RFMOs, particularly regarding the inclusion of impacts across multiple sectors in impact assessments for areas beyond national jurisdiction (Johnson *et al*., 2025). Sectors identified as being a priority for immediate inclusion in cumulative impacts assessment include biodiversity conservation, climate change, oil and gas, and deep-sea mining and renewable energy (Johnson *et al*., 2025). The BBNJ Agreement sets out the procedures for proposals for area-based management tools (*e.g.*, marine protected areas, fishery closures), which are expected to be formally assessed. These proposals are likely to include criteria for identifying areas of ecological significance and consideration of fishing impacts, alongside other anthropogenic pressures. Such criteria are likely to relate directly to VMEs and assessment of SAIs, respectively. Therefore, future impact assessments would benefit from a standardised framework (similar to, or based on the BFIAS, for example) and build on the significant progress SPRFMO has made in developing and implementing

Standards and Conservation and Management Measures intended to safeguard the marine ecosystems in which the fishing resources it manages occur. In this context, promoting increased cooperation at regional scales between established RFMOs such as SPRFMO and other inter-governmental organisations appears to be critical to achieve broader conservation and sustainability goals (Carmine *et al*., 2025; FAO, 2026; Johnson *et al*., 2025; Tian and Guo, 2025; Weiand *et al*., 2021).

Acknowledgements

We thank Riki Mules from the New Zealand Ministry for Primary Industries for providing us with his geospatial expertise and support.

We thank the New Zealand Ministry for Primary Industries (including its fisheries business unit, Fisheries New Zealand), the Ministry of Foreign Affairs and Trade and the Department of Conservation for their involvement in the inception and on-going work of SPRFMO.

We thank the many people who along the way have been involved in the development of the science and the measures that inform an ecosystem approach to deep-sea fisheries management in the SPRFMO Convention Area, including all participants (past and present) of the SPRFMO Deepwater Working Group and of the New Zealand South Pacific Working Group (SPACWG), former chair of the Scientific Committee James Ianelli, and former chair of the International Consultations and Preparatory Conference, Bill Mansfield.

We thank NAFO, ICES and the Food and Agriculture Organization (FAO) of the United Nations for co-organising and hosting the Symposium on applying the Ecosystem Approach to Fisheries Management in ABNJ, 11–13 March 2025 at the FAO Headquarters in Rome. We thank Anthony Thompson, Eszter Hidas and Keith Reid for their continuous support of the FAO Deep-sea Fisheries Project and its on-going engagement with SPRFMO.

Finally, we thank Andie Perreault (General Editor, JNAFS) and the anonymous reviewers for providing constructive comments that improved our manuscript.

References

Anderson, O., Charsley, A., Moore, B., Rowden, A., Bennion, M., Tablada, J., Geange, S., and Arkhipkin, A. 2024. Updated quantitative benthic impact assessment for New Zealand and Australian bottom fisheries. South Pacific Regional Fisheries Management Organisation, SC12-DW12. https://www.sprfmo.int/assets/Meetings/02-SC/12th-SC-2024/Deepwater/SC12-DW12_rev1-NZL-Updated-quantitative-benthic-impact-assessment-for-New-Zealand-and-Australian-bottom-fisheries.pdf

Anderson, O. F., Stephenson, F., Behrens, E., and Rowden, A. A. 2022. Predicting the effects of climate change on deep-water coral distribution around New Zealand—Will there be suitable refuges for protection at the end of the 21st century? *Global Change Biology*, **28**: 6556– 6576. https://doi.org/10.1111/gcb.16389

Anderson, J. L., Anderson, C. M., Chu, J., Meredith, J., Asche, F., Sylvia, G., Pinto da Silva, P., Tlusty, M., Garcia, E., Cleary, J., and Morrissey, M. T. 2015. The Fishery Performance Indicators: A management tool for triple bottom line outcomes. *PLOS ONE*, **10(5)**: e0122809. https://doi.org/10.1371/journal.pone.0122809

Ardron, J. A., Clark, M. R., Penney, A. J., Hourigan, T. F., Rowden, A. A., Dunstan, P. K., Watling, L., Shank, T. M., Tracey, D. M., Dunn, M. R., and Parker, S. J. 2014. A systematic approach towards the identification and protection of vulnerable marine ecosystems. *Marine Policy*, **49**: 146–154. https://doi.org/10.1016/j.marpol.2013.11.017

Arkhipkin, A., and Tablada, J. 2025. Revision of SPRFMO Bottom Fishing Impact Assessment Standard. South Pacific Regional Fisheries Management Organisation, SC13-DW11. https://www.sprfmo.int/assets/Meetings/02-SC/13th-SC-2025/Deepwater/SC13-DW11-Revision-of-SPRFMO-Bottom-Fishing-Impact-Assessment-Standard.pdf

Baco, A. R., Ross, R., Althaus, F., Amon, D., Bridges, A. E. H. Brix, S., Buhl-Mortensen, P., Colaco, A., Carreiro-Silva, M., Clark, M. R., Du Preez, C., Franken, M-L., Gianni, M., Gonzalez-Mirelis, G., Hourigan, T., Howell, K., Levin, L. A., Lindsay, D. J., Molodtsova, T. N., Morgan, N., Morato, T., Mejia-Mercado, B. E., O'Sullivan, D., Pearman, T., Price, D., Robert, K., Robson, L., Rowden, A. A., Taylor, J., Taylor, M., Victorero, L., Watling, L., Williams, A., Xavier, J. R., and Yesson, C. 2023. Towards a scientific community consensus on designating Vulnerable Marine Ecosystems from imagery. *PeerJ,* **11**: e16024 https://doi.org/10.7717/peerj.16024

Behrens, E., Williams, J., Morgenstern, O., Sutton, P., Rickard, G., and Williams, M. J. 2020. Local grid refinement in New Zealand's earth system model: Tasman Sea ocean circulation improvements and super-gyre circulation implications. *Journal of Advances in Modeling Earth Systems,* **12**: e2019MS001996. https://doi.org/10.1029/2019MS001996

Bennion, M., Anderson, O. F., Rowden, A. A., Bowden, D. A., Geange, S. W., and Stephenson, F. 2024. Evaluation of the full set of habitat suitability models for vulnerable marine ecosystem indicator taxa in the South Pacific high seas. *Fisheries Management and Ecology*, **31(4)**: e12700. https://doi.org/10.1111/fme.12700

Bennion, M., Rowden, A. A., Anderson, O. F., Bowden, D. A., Clark, M. R., Althaus, F., Williams, A., Geange, S. W., Tablada, J., and Stephenson, F. 2025a. The Use of Image-Based Data and Abundance Modelling Approaches for Predicting the Location of Vulnerable Marine Ecosystems in the South Pacific Ocean. *Fisheries Management and Ecology*, **32(1)**: e12751. https://doi.org/10.1111/fme.12751

Bennion, M., Rowden, A. A., Moore, B. R., Anderson, O. F., Tablada, J., Geange, S. W., and Stephenson, F. 2025b. Development of the South Pacific Vulnerable Marine Ecosystem bioregionalisation. *Frontiers in Ecology* *and Evolution*, **13**: 1670027. https://doi.org/10.3389/fevo.2025.1670027

Brough, T., Bennion, M., Leunissen, E., Hayden, M., and Behrens, E. 2025. Forecasting future habitat suitability of marine taxa to advance climate-smart marine spatial planning in Aotearoa New Zealand. NIWA CLIENT REPORT No: 2025186HN Prepared for the Department of Conservation. https://www.doc.govt.nz/globalassets/documents/conservation/marine-and-coastal/marine-protected-areas/forecasting-future-habitat-suitability-of-marine-taxa-to-advance-climate-smart-marine-spatial-planning.pdf

Carmine, G., Cronin, M. R., Barkley, C., Tuohy, C. L., Crespo, G.O., Österblom, H., Jacquet, J. and Halpin, P. N. 2025. An expanded evaluation of global fisheries management organizations on the high seas. *Environmental Research Letters*, **20(12)**: 123001. https://doi.org/10.1088/1748-9326/ae1b1e

Cerutti-Pereyra, F., Drenkard, E.J., Espinoza, M., Finucci, B., Galván-Magaña, F., Hacohen-Domené, A., Hearn, A., Hoyos-Padilla, M. E., Ketchum, J. T., Mejía-Falla, P. A. and Moya-Serrano, A. V. 2024. Vulnerability of Eastern Tropical Pacific chondrichthyan fish to climate change. *Global Change Biology*, **30(7)**: e17373. https://doi.org/10.1111/gcb.17373

Clark, M. R., and Roberts, C. D. 2008. Fish and invertebrate biodiversity on the Norfolk Ridge and Lord Howe Rise, Tasman Sea (NORFANZ voyage, 2003). *New Zealand Aquatic Environment and Biodiversity Report* **No. 28**. 131 p. https://webstatic.niwa.co.nz/library/NZAEBR28.pdf

Clark, M. R., Anderson, O. F., Bowden, D. A., Chin, C., George, S. G., Glasgow, D. A., Guinotte, J. M., Hererra, S., Osterhage, D. M., Pallentin, A., Parker, S. J., Rowden, A. A., Rowley, S. J., Stewart, R., Tracey, D. M., Wood, S. A., and Zeng, C. 2015. Vulnerable Marine Ecosystems of the Louisville Seamount Chain: voyage report of a survey to evaluate the efficacy of preliminary habitat suitability models. *New Zealand Aquatic Environment and Biodiversity Report* **No. 149**: 86 p. https://fs.fish.govt.nz/Doc/23779/AEBR_149_2848_SEA2013-01%20.pdf.ashx

Clark, M.R ., Wood, B., Mackay, K., Anderson, O. F., Hart, A., Rickard, G., and Rowden, A. A. 2022. Underwater Topographic Features in the New Zealand region: development of an updated 'SEAMOUNT' database and information on the extent and intensity of deep-sea trawl fisheries on them. *New Zealand Aquatic Environment and Biodiversity Report* **No. 291**: 28 p. https://fs.fish.govt.nz/Doc/25301/AEBR-291-Underwater-Topographic-Features-SEAMOUNT-Database-NZ-Region-4268.pdf.ashx

Cooke, S. J., Fulton, E. A., Sauer, W. H. H., Lynch, A. J., Link, J. S., Koning, A. A., Jena, J., Silva, L. G. M., King, A. J., Kelly, R., Osborne, M., Nakamura, J., Preece, A. L., Hagiwara, A., Forsberg, K., Kellner, J. B., Coscia, I., Helyar, S., Barange, M., Nyboer, E., Williams, M. J., Chuenpagdee, R., Begg, G. A., and Gillanders, B. M. 2023. Towards vibrant fish populations and sustainable fisheries that benefit all: learning from the last 30 years to inform the next 30 years. *Rev. Fish. Biol. Fisheries,* **33**: 317–347. https://doi.org/10.1007/s11160-023-09765-8

Cryer, M., Geange, S. W., and Bock, T. 2018. Methods for Designing Spatial Management Areas Using Outputs from Zonation Software and Other Spatial Data. South Pacific Regional Fisheries Management Organisation, SC6-DW11. https://sprfmo.int/assets/Meetings/02-SC/2018-SC6/Meeting-Documents/SC6-DW11-Process-for-drawing-mgmt-areas.pdf

Cummings, V. J., Lundquist, C. J., Dunn, M. R, Francis, M., Horn, P., Law, C., Pinkerton, M. H., Sutton, P., Tracey, D., Hansen, L., and Mielbrecht, E. 2021. Assessment of potential effects of climate-related changes in coastal and offshore waters on New Zealand's seafood sector. *New Zealand Aquatic Environment and Biodiversity Report* **No. 261**: 153 p. https://fs.fish.govt.nz/Doc/24891/AEBR-261-Assessment-Of-Potential-Effects-Of-Climate-Change-On-Seafood-Sector-3389.pdf.ashx

Curtis, J. M., Rooper, C. N., and Warawa, D. R. 2020. A Framework for Identifying Vulnerable Marine Ecosystems in the North Pacific Ocean. North Pacific Fisheries Commission, BFME01-WP12. https://www.npfc.int/system/files/2020-11/NPFC-2020-SSC%20BFME01-WP12%20A%20Framework%20for%20Identifying%20Vulnerable%20Marine%20Ecosystems.pdf

Datta, S., Beran, H., and Rogers, A. 2024. The impacts of warming on shallow and deep-water fisheries in New Zealand. *Earth's Future*, **12(12)**: e2024EF004857. https://doi.org/10.1029/2024EF004857

De Clippele, L. H., Nozères, C., Xu, J., MacDonald, B., Lirette, C., Phelan, K., Staniford, C., Whoriskey, F., Wolff, G. A., Blackbird, S., Mohn, C. and Kenchington, E. 2025. Fish use of deep-sea sponge habitats evidenced by long-term high-resolution monitoring. *Scientific reports*, **15**: 17656. https://doi.org/10.1038/s41598-025-01822-5

De Clippele, L. H., Rovelli, L., Ramiro-Sánchez, B., Kazanidis, G., Vad, J., Turner, S., Glud, R. N., and Roberts, J. M. 2021. Mapping cold-water coral biomass: an approach to derive ecosystem functions. *Coral Reefs*, **40(1)**: 215–231. https://doi.org/10.1007/s00338-020-02030-5

Durán Muñoz, P., Abalo Morla, S., Palas Otero, S., Garrido Fernández, I., Baldó Martínez, F., Sacau Cuadrado, M. 2022. NEREIDA: Research in support of the reassessment of NAFO bottom fisheries in 2022, Project number 101074766. https://www.nafo.int/Portals/0/PDFs/NEREIDA/NEREIDA_Final_Report_with_Annexes.pdf

DOSI. 2022. Assessments for Deep-Sea Fisheries on the High Seas against the FAO Deep-Sea Fisheries Guidelines. *Deep Ocean Stewardship Initiative Report*. https://www.dosi-project.org/fisheries-review-2022

FAO. 2019. Deep-ocean climate change impacts on habitat, fish and fisheries, Lisa Levin, Maria Baker, and Anthony Thompson (Eds.). *FAO Fisheries and Aquaculture Technical Paper* **No. 638**: Rome, FAO. 186 p. https://openknowledge.fao.org/handle/20.500.14283/ca2528en

FAO. 2012. EAF Toolbox: The ecosystem approach to fisheries. Rome. 172 p. https://openknowledge.fao.org/handle/20.500.14283/cc6834en

FAO. 2026. Fisheries and the BBNJ Agreement – A guide. The Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable

Use of Marine Biological Diversity of Areas beyond National Jurisdiction (BBNJ Agreement). Rome. https://doi.org/10.4060/cd7986en

FAO. 2009. International Guidelines for the Management of Deep- Sea Fisheries in the High-seas. Food and Agriculture Organisation of the United Nations, Rome, Italy, 73 p. https://openknowledge.fao.org/handle/20.500.14283/i0816t

Fletcher, W. J. 2020. A review of the application of the FAO ecosystem approach to fisheries (EAF) management within the areas beyond national jurisdiction (ABNJ). Rome, FAO. https://www.fao.org/3/cb1509en/CB1509EN.pdf

Free, C. M., Mangin, T., García Molinos, J., Ojea, E., Burden, M., Costello, C., and Gaines, S. D. 2020. Realistic fisheries management reforms could mitigate the impacts of climate change in most countries. *PLOS ONE*, **15(3)**: e0224347. https://doi.org/10.1371/journal.pone.0224347

Gammon, M. J., Tracey, D. M., Marriott, P. M., Cummings, V. J., and Davy, S. K. 2018. The physiological response of the deep-sea coral *Solenosmilia variabilis* to ocean acidification. *PeerJ,* **6**: e5236. https://doi.org/10.7717/peerj.5236

Garcia, S. M., and Cochrane, K. L. 2005. Ecosystem approach to fisheries: a review of implementation guidelines. *ICES Journal of Marine Science*, **62(3)**: 311–318. https://doi.org/10.1016/j.icesjms.2004.12.003

Geange, S. W., Rowden, A. A., Cryer, M., and Bock, T. D. 2019. Evaluating the availability of data to assess catchability of VME indicator taxa. South Pacific Regional Fisheries Management Organisation, SC7-DW14. https://www.sprfmo.int/assets/Meetings/SC/7th-SC-2019/SC7-DW14-Availability-of-Data-to-Assess-Catchability-of-VME-Indicator-Taxa.pdf

Geange, S. W., Rowden, A. A., Nicol, S., Bock, T., and Cryer, M. 2020. A data-informed approach for identifying move-on encounter thresholds for vulnerable marine ecosystem indicator taxa. *Frontiers in Marine Science*, **7**: 155 p. https://doi.org/10.3389/fmars.2020.00155

Georgeson, L., and Cryer, M. 2019. Revision of the SPRFMO Bottom Fishery Impact Assessment Standard. South Pacific Regional Fisheries Management Organisation, SC7-DW19. https://www.sprfmo.int/assets/Meetings/SC/7th-SC-2019/SC7-DW19-Revision-of-SPRFMO-Bottom-Fishing-Impact-Assessment-Standard.pdf

Georgeson, L., Nicol, S., Cryer, M., and Bock, T. 2018. Review of the SPRFMO Bottom Fishery Impact Assessment Standard. South Pacific Regional Fisheries Management Organisation, SC6-DW13. https://www.sprfmo.int/assets/Meetings/02-SC/2018-SC6/Meeting-Documents/SC6-DW13-SPRFMO-BFIAS-review.pdf

Grantham, H., Adams, V., and The IUCN WCPA Taskforce on Spatial Planning. 2024. An overview of Participatory, Integrated, and Biodiversity-Inclusive Spatial Planning and Target 1 under the Convention on Biological Diversity Kunming-Montreal Global Biodiversity Framework, *IUCN WCPA Issues Paper Series,* **No. 4**, Gland, Switzerland: IUCN. https://iucn.org/sites/default/files/2024-10/iucn-wcpa-issues-paper-4.pdf

Hiddink, J. G., Valanko, S., Delargy, A. J., and van Denderen, P. D. 2023. Setting thresholds for good ecosystem state in marine seabed systems and beyond. *ICES Journal of Marine Science*, **80**: 698–709. https://doi.org/10.1093/icesjms/fsad035

Hitt, N. T., Sinclair, D. J., Fallon, S. J., Neil, H. L., Tracey, D. M., Komugabe-Dixson, A., and Marriott, P. 2020. Growth and longevity of New Zealand black corals. *Deep Sea Research Part I: Oceanographic Research Papers*, **162**: 103298. https://doi.org/10.1016/j.dsr.2020.103298

Hobday, A. J., Smith, A. D. M, Stobutzki, I. C., Bulman, C., Daley, R., Dambacher, J. M., Deng, R. A., Dowdney, J., Fuller, M., Furlani, D., Griffiths, S. P., Johnson, D., Kenyon, R., Knuckey, I. A., Ling, S. D., Pitcher, R., Sainsbury, K. J., Sporcic, M., Smith, T., Turnbull, C., Walker, T. I., Wayte, S. E., Webb, H., Williams, A., Wise, B. S., and Zhou, S. 2011. Ecological risk assessment for the effects of fishing. *Fisheries Research*. Volume **108: Issues 2–3**. https://doi.org/10.1016/j.fishres.2011.01.013

Hobday, A. J., J. Dowdney, C. Bulman, M. Sporcic, M. Fuller, M. Goodspeed, and E. Hutchinson. 2007. Ecological Risk Assessment for the Effects of Fishing: Bass Strait Central Zone Scallop Sub-Fishery. Report for the Australian Fisheries Management Authority, Canberra. https://www.fish.gov.au/Archived-Reports/2014/Documents/2014_refs/Hobday%20et%20al%202007%20ERA.pdf

ICES. 2022. Benchmark Workshop on the occurrence and protection of VMEs (vulnerable marine ecosystems) (WKVMEBM). *ICES Scientific Reports*. **4:55**. 99 p. http://doi.org/10.17895/ices.pub.20101637

ICES. 2024. NEAFC request on Ecosystem Approaches to Fisheries Management. ICES Advice: Special Requests. Report. https://doi.org/10.17895/ices.advice.27052372.v1

Johnson, D. E., Turner, P. J., and Barrio Froján, C. 2025. Report on cross-sectoral impacts on deep-sea fisheries in the high seas. Rome, FAO. https://doi.org/10.4060/cd3781en

Judah, A. B., Mull, C. G., Dulvy, N. K., Finucci, B., Assad, V. E., and Drazen, J. C. 2025. Deep-sea mining risks for sharks, rays, and chimaeras. *Current Biology*, **35(21)**: 5353–5362. https://doi.org/10.1016/j.cub.2025.09.019

Kaikkonen, L., Amaro, T., Auster, P.J., Bailey, D. M., Bell, J. B., Brandt, A., Clark, M. R., Drazen, J. C., Du Preez, C., Escobar-Briones, E., Giacomello, E., Gianni, M., Johnson, A. F., Levin, L. A., Milligan, R. J., Oduware, S., Pearman, T. R. R., Pham, C. K., Ramalho, S. P., Rowden, A. A., Sutton, T. T., Taylor, M. L., Watling, L., and Victorero, L. 2024. Improving impact assessments to reduce impacts of deep-sea fisheries on vulnerable marine ecosystems. *Marine Policy*, Volume **167**: 106281. https://doi.org/10.1016/j.marpol.2024.106281

Keller, K, Emery, T, Timmiss, T., Hartog, J., and Fuller, M. 2025. Updated SPRFMO ecological risk assessment for teleost and deepwater chondrichthyans. South Pacific Regional Fisheries Management Organisation, SC13-DW03. https://www.sprfmo.int/assets/Meetings/02-SC/13th-SC-2025/Deepwater/SC13-DW03-Ecological-Risk-Assessment-for-Deepwater-fisheries.pdf

Kenchington, E., Lirette, C., Sacau, M., Murillo, F. J., and Wang, Z. 2026. Vulnerable marine ecosystems in the NAFO regulatory area: Updated Kernel Density analyses of vulnerable marine ecosystem indicators. *NAFO SCR Doc.*, **25/047**, Serial No. N7693. https://doi.org/10.13140/RG.2.2.10484.00649

Kenny, A. J., Pepin, P., Bell, J., Downie, A., Kenchington, E., Koen-Alonso, M., Lirette, C., Barrio Froján, C., Ollerhead, Neil., Murillo, F. J., Sacau, M., Fuller, S. and Diz, D. 2025. Reference points for assessing significant adverse impacts on deep sea vulnerable marine ecosystems. *Ecological Indicators*, **172**: 113296. https://doi.org/10.1016/j.ecolind.2025.113296

Kirby, D. S., and Ward, P. 2014. Standards for the effective management of fisheries bycatch. *Marine Policy*, **44**: 419–426. https://doi.org/10.1016/j.marpol.2013.10.008

Koen-Alonso, M., Pepin, P., Fogarty, M. J., Kenny, A., and Kenchington, E. 2019. The Northwest Atlantic Fisheries Organization Roadmap for the development and implementation of an Ecosystem Approach to Fisheries: structure, state of development, and challenges. *Marine Policy*, **100**: 342–352. https://doi.org/10.1016/j.marpol.2018.11.025

Maier, S. R., Kutti, T., Bannister, R. J., Fang, J. K. H., van Breugel, P., van Rijswijk, P., and Van Oevelen, D. 2020. Recycling pathways in cold-water coral reefs: Use of dissolved organic matter and bacteria by key suspension feeding taxa. *Scientific reports*, **10(1)**: 9942. https://doi.org/10.1038/s41598-020-66463-2

Marine Stewardship Council 2024. MSC Fisheries Standard Version 3.1. https://www.msc.org/standards-and-certification/fisheries-standard/version-3

McCay, B. J., and Jentoft, S. 1996. From the bottom up: Participatory issues in fisheries management. *Society & Natural Resources*, **9(3)**: 237–250. https://doi.org/10.1080/08941929609380969

Morato, T., Pham, C. K., Pinto, C., Golding, N., Ardron, J. A., Durán Muñoz, P., and Neat, F. 2018. A multi criteria assessment method for identifying vulnerable marine ecosystems in the North-East Atlantic. *Frontiers in Marine Science*, **5**:460. https://doi.org/10.3389/fmars.2018.00460

Milardi, M., and Geange, S. W. 2021. Design of a review process for VME encounters in bottom fisheries in the SPRFMO Area. South Pacific Regional Fisheries Management Organisation, SC9-DW08. https://www.sprfmo.int/assets/Meetings/SC/9th-SC-2021/deepwater-wg/SC9-DW08-Design-of-a-review-process-for-VME-encounters-in-bottom-fisheries-in-the-SPRFMO-area.pdf

NAFO. 2020. Report of the 13th Meeting of the NAFO Scientific Council Working Group on Ecosystem Science and Assessment (WG-ESA). *NAFO SCS Doc.* **20/23**, Serial No. 7148. https://www.nafo.int/Portals/0/PDFs/sc/2020/scs20-23.pdf

New Zealand. 2025. New Zealand 2024 VME Encounter Review. South Pacific Regional Fisheries Management Organisation, SC13-DW09. https://www.sprfmo.int/assets/Meetings/02-SC/13th-SC-2025/Deepwater/SC13-DW09-New-Zealand-2024-VME-Encounter-Review.pdf .

Peixoto, U. I., Sporcic, M., Hobday, A. J., Bentes, B., Passarone, R., Fredou, F. L., and Isaac, V. J. 2025. Ecological risk assessment of marine resources caught as bycatch in industrial bottom trawl shrimp fishery in the Amazon Continental Shelf. *Frontiers in Marine Science*, **12**: 1490894. https://doi.org/10.3389/fmars.2025.1490894

Penney, A. J. 2014. Review of the biodiversity component of the New Zealand Vulnerable Marine Ecosystem Evidence Process. *New Zealand Aquatic Environment and Biodiversity Report* **No. 135**. 40 p. https://www.mpi.govt.nz/dmsdocument/4723/direct/

Pentz, B., Klenk, N., Ogle, S., and Fisher, J. A. 2018. Can regional fisheries management organizations (RFMOs) manage resources effectively during climate change?. *Marine Policy*, **92**: 13–20. https://doi.org/10.1016/j.marpol.2018.01.011

Pinkerton, M. H. 2017. Impacts of Climate Change on New Zealand Fisheries and Aquaculture. *In* Climate Change Impacts on Fisheries and Aquaculture (Eds. B. F. Phillips and M. Pérez-Ramírez). https://doi.org/10.1002/9781119154051.ch5

Pitcher, C. R., Ellis, N., Jennings, S., Hiddink, J. G., Mazor, T., Kaiser, M. J., Kangas, M. I., McConnaughey, R. A., Parma, A. M., and Rijnsdorp, A. D. 2017. Estimating the sustainability of towed fishing-gear impacts on seabed habitats: a simple quantitative risk assessment method applicable to data- limited fisheries. *Methods in Ecology and Evolution*, **8(4)**: 472–480. https://doi.org/10.1111/2041-210X.12705

Reid, K. 2023. A review of the basis by which RFMOs have determined VME encounter thresholds by taxa and gear-types. North Pacific Fisheries Commission, 4th Small Scientific Committee on Bottom Fish and Marine Ecosystems (SSC BF-ME) meeting. https://www.npfc.int/system/files/2023-11/NPFC-2023-SSC%20BFME04-WP06%20VME%20encounter%20thresholds.pdf

Rooper, C. N., Somers, K., Goddard, P., and Campbell, G. 2025. Estimating quantitative gear and taxa specific encounter thresholds for commercial fisheries bycatch of vulnerable marine ecosystem indicator taxa. *Deep Sea Research Part II: Topical Studies in Oceanography*, **219**: 105448. https://doi.org/10.1016/j.dsr2.2024.105448

Rowden, A. A., Anderson, O. F., Stephenson, F., Geange, S. W., and Milardi, M. 2025. Determination of optimal move-on distance for trawl encounters with vulnerable marine ecosystems. *ICES Journal of Marine Science*, **82(2)**: fsae173. https://doi.org/10.1093/icesjms/fsae173

Rowden, A. A., Stephenson, F., Cryer, M., Lundquist, C. J., Anderson, O. F., Bennion, M., Biggerstaff, A., Bock, T., Brough, T., Georgeson, L., Macdonald, A., Milardi, M., Nicol, S., Pitcher, R., Tablada, J., Timmiss, T. A., Magsig, R. M., and Geange, S. W. 2026. Implementing area-based management of vulnerable marine ecosystems in areas beyond national jurisdiction: A South Pacific case study. Ocean & Coastal Management, 280, 108267. https://doi.org/10.1016/j.ocecoaman.2026.108267

Rowden, A., Tablada, J., and Arkhipkin, A. 2024. A review of information to assist in defining thresholds for significant adverse impact on vulnerable marine ecosystems. South Pacific Regional Fisheries Management Organisation, SC12-DW07_rev1. https://www.sprfmo.int/assets/Meetings/02-SC/12th-SC-2024/Deepwater/SC12-DW07_rev1-NZL-A-review-of-information-to-assist-in-defining-

thresholds-for-SIAs-on-VMEs.pdf
Sharp, B. R., Parker, S. J. and Smith, N. 2009. An impact assessment framework for bottom fishing methods in the CAMLR Convention Area. *CCAMLR Science*, **16**: 195–210. https://www.ccamlr.org/en/system/files/science_journal_papers/10sharp-et-al.pdf
SPRFMO. 2025a. Conservation and Management Measure for the Management of Bottom Fishing in the SPRFMO Convention Area (CMM 03-2025). South Pacific Regional Fisheries Management Organisation. https://www.sprfmo.int/assets/Fisheries/Conservation-and-Management-Measures/2025-CMMs/CMM-03-2025-Bottom-Fishing.pdf
SPRFMO. 2025b. Conservation and Management Measure on Standards for the Collection, Reporting, Verification and Exchange of Data (CMM 02-2025). South Pacific Regional Fisheries Management Organisation. https://www.sprfmo.int/assets/Fisheries/Conservation-and-Management-Measures/2019-CMMs/031708aaea/CMM-03-2019-5Mar2019.pdf
SPRFMO. 2025c. 13th Scientific Committee meeting report 180 p. Wellington, New Zealand 2025. South Pacific Regional Fisheries Management Organisation, SC13. https://www.sprfmo.int/assets/Meetings/02-SC/13th-SC-2025/SC13-REPORT-ADOPTED-13SEPT2025b.pdf
SPRFMO. 2024. Encounter Review Standard for the South Pacific Regional Fisheries Management Organisation. South Pacific Regional Fisheries Management Organisation. https://sprfmo.int/assets/Meetings/02-SC/12th-SC-2024/Deepwater/SC12-DW10-NZL-Encounter-Review-Standard-for-the-SPRFMO.pdf
SPRFMO. 2023. Cumulative Bottom Fishery Impact Assessment for Australian and New Zealand bottom fisheries, 2023. Prepared by Australia and New Zealand. South Pacific Regional Fisheries Management Organisation, SC11 – DW01_rev1. https://www.sprfmo.int/assets/Meetings/02-SC/11th-SC-2023/Deepwater/SC11-DW01_rev1-Cumulative-Bottom-Fishery-Impact-Assessment-for-AUS-and-NZL-bottom-fisheries-2023.pdf
SPRFMO. 2019a. Bottom Fishery Impact Assessment Standard for the South Pacific Regional Fisheries Management Organisation. South Pacific Regional Fisheries Management Organisation. https://www.sprfmo.int/assets/Fisheries/Science/SPRFMO-Bottom-Fishery-Impact-Assessment-Standard-2019.pdf
SPRFMO. 2019b. Conservation and Management Measure for the Management of Bottom Fishing in the SPRFMO Convention Area (CMM 03-2019). South Pacific Regional Fisheries Management Organisation. https://www.sprfmo.int/assets/Fisheries/Conservation-and-Management-Measures/2019-CMMs/031708aaea/CMM-03-2019-5Mar2019.pdf
SPRFMO. 2022. Convention on the Conservation and Management of High Seas Fishery Resources in the South Pacific Ocean. South Pacific Regional Fisheries Management Organisation. https://www.sprfmo.int/assets/Basic-Documents/Convention-and-Final-Act/SPRFMO-Convention-2023-update-12May2023.pdf
SPRFMO. 2014. Conservation and Management Measure for the Management of Bottom Fishing in the SPRFMO Convention Area (CMM 2.03). South Pacific Regional Fisheries Management Organisation. https://www.sprfmo.int/assets/Meetings/Archived-Meetings/Meetings-2013-plus/Commission-Meetings/2nd-Commission-Meeting-2014-Manta-Ecuador/Annex-M-CMM-2.03-CMM-for-Bottom-Fishing.pdf
SPRFMO. 2012. Bottom Fishery Impact Assessment Standard. South Pacific Regional Fisheries Management Organisation. https://www.sprfmo.int/assets/Meetings/Meetings-before-2013/Scientific-Working-Group/SWG-06-2008/a-Miscellaneous-Documents/4daf89abbe/SPRFMO-Bottom-Fishing-Impact-Assessment-Standardagreed-Vanuatu-Fri23Sep2011-1140am.pdf
SPRFMO. 2009a. Revised Draft Bottom Fishery Impact Assessment Standard (SP-08-SWG-DW-01). South Pacific Regional Fisheries Management Organisation, SWG-08-DW01. https://www.sprfmo.int/assets/Meetings/Meetings-before-2013/Scientific-Working-Group/SWG-08-2009/6829ec9d63/SP-08-SWG-DW-01-Revised-draft-SPRFMO-Bottom-Fishing-Impact-Assessment-Standard.doc.pdf
SPRFMO. 2009b. Standards for the collection, reporting, verification and exchange of data. South Pacific Regional Fisheries Management Organisation. https://sprfmo.int/assets/Fisheries/Old-Interim-Measures-Reporting/35a811a40b/2009May18-SPRFMO7-Annex-DConsolidated-Data-Standards-Amended-Peru.pdf
SPRFMO. 2008. Bottom Fishery Impact Assessment Bottom Fishing Activities by New Zealand Vessels Fishing in the High Seas in the SPRFMO Area during 2008 and 2009. South Pacific Regional Fisheries Management Organisation. https://www.sprfmo.int/assets/Meetings/Meetings-before-2013/Scientific-Working-Group/SWG-06-2008/a-Miscellaneous-Documents/c072db6780/New-Zealand-Bottom-Fishery-Impact-Assessment-v1.3-2009-05-13.pdf
Stephenson, F., Zelli, E., Bennion, M., Rowden, A. A., Anderson, O. F., Clark, M. R., Tablada, J., Hiddink, J. G., Kaikkonen, L., Finucci, B. and Tracey, D.M., and Geange, S. W. 2025. Large-scale assessments of bottom trawling effects on Vulnerable Marine Ecosystems can significantly under-represent impacts. *Journal of Environmental Management,* **395**, 127672. https://doi.org/10.1016/j.jenvman.2025.127672
Stephenson, F., Rowden, A. A., Anderson, O. F., Ellis, J. I., Geange, S.W., Brough, T., Behrens, E., Hewitt, J.E., Clark, M. R., Tracey, D. M. and Goode, S. L., 2023. Implications for the conservation of deep-water corals in the face of multiple stressors: A case study from the New Zealand region. *Journal of Environmental Management*, **346**: 118938. https://doi.org/10.1016/j.jenvman.2023.118938
Stephenson, F., Geange, S., Rowden, A., Charsley, A., Anderson, O., and Biggerstaff, A. 2022. Further analysis of the catchability of VME indicator taxa and the design of a related research programme. South Pacific Regional Fisheries Management Organisation, SC10-DW04. https://www.sprfmo.int/assets/Meetings/SC/10th-SC-2022/SC10-DW04-Further-analysis-of-VME-indicator-taxa-catchability-and-the-design-of-a-related-research-programme-NZ.pdf

Stephenson, F., Rowden, A. A., Anderson, O. F., Pitcher, C. R., Pinkerton, M. H., Petersen, G., and Bowden, D. A. 2021. Presence-only habitat suitability models for vulnerable marine ecosystem indicator taxa in the South Pacific have reached their predictive limit. *ICES Journal of Marine Science*, **78(8)**: 2830–2843. https://doi.org/10.1093/icesjms/fsab162

Susini, I., Van Audenhaege, L., Price, D. M., Pearman, T. R., Mitchell, E. G., and Huvenne, V. A. 2025. Fine-scale spatial organisation of deep-sea sea pens in a NE Atlantic submarine canyon conservation area. *Scientific Reports*, **15(1)**: 29332. https://doi.org/10.1038/s41598-025-13327-2

Tablada, J., Geange, S., and Stephenson, F. 2022. Development of a process to review all recent and historical benthic bycatch data. South Pacific Regional Fisheries Management Organisation, SC10-DW03. https://www.sprfmo.int/assets/Meetings/SC/10th-SC-2022/SC10-DW03-Development-of-a-process-to-review-all-recent-and-historical-benthic-bycatch-data-NZ.pdf

Tablada, J., Jefferson, T., Tunley, K., and Geange, S. 2023. Development of a process to review all recent and historical benthic VME bycatch data. South Pacific Regional Fisheries Management Organisation, SC11-DW10. https://www.sprfmo.int/assets/Meetings/02-SC/11th-SC-2023/Deepwater/SC11-DW10-NZL-Development-of-a-process-to-review-all-recent-and-historical-benthic-VME-bycatch-data.pdf

Thompson, A. B., and Reid, K. 2024. Review of the implementation of the International Guidelines for the Management of Deep-sea Fisheries in the High Seas. *FAO Fisheries and Aquaculture Technical Paper*, **No. 703**. Rome, FAO. https://doi.org/10.4060/ca7692en

Tian, H., and Guo, J. 2025. The potential interactions between the BBNJ Agreement and RFMOs in the establishment of ABMTs: Implications for RFMOs. *Marine Policy*, **171**: 106477. https://doi.org/10.1016/j.marpol.2024.106477

Tingley, G., and Dunn, M. 2018. Global review of orange roughy (*Hoplostethus atlanticus*), their fisheries, biology and management. FAO. https://openknowledge.fao.org/handle/20.500.14283/ca1870en

Tracey, D. M., Marriott, P., Hitt, N., Neil, H., and Clark, M. R. 2024. Age and growth of a habitat-forming deep-sea coral *Solenosmilia variabilis* in the New Zealand region: implications for fisheries management. *New Zealand Journal of Marine and Freshwater Research*, **59(5)**: 997–1019. https://doi.org/10.1080/00288330.2024.2398779

Turschwell, M. P., Brown, C. J., Lacharité, M., Melbourne-Thomas J., Hayes, K. R., Bustamante, R. H., Dambacher, J. M., Evans, K., Fidelman, P., MacDonald, D. H., Van Putten, I., Wood, G., Abdussamie, N., Bates, M., Blackwell, D., D'Alessandro, S., Dutton, I., Ericson, J. A., Frid, C. L. J., McDougall, C.,Lea, M.-A., Rissik, D., Trebilco, R., and Fulton, E. A. 2023. Co-designing a multi-criteria approach to ranking hazards to and from Australia's emerging offshore blue economy. *Environmental Science & Policy*, **147**: 154–168. https://doi.org/10.1016/j.envsci.2023.06.008

van Denderen, P. D., Holah, H., Robson, L. M., Hiddink, J. G., Menot, L., Pedreschi, D., Kazanidis, G., Llope, M., Turner, P. J., Stirling, D., Murillo, F. J., Kenny, A., Campbell, N., Allcock, A. L., Braga-Henriques, A., González-Irusta, J. M., Johnston, G., Orejas, C., Serrano, A., Xavier, J. R., Hopkins, P., Kenchington, E., Nixon, E., and Valanko, S. A. 2022. Policy-based framework for the determination of management options to protect vulnerable marine ecosystems under the EU deep-sea access regulations. *ICES Journal of Marine Science*, **79**: 34–49. https://doi.org/10.1093/icesjms/fsab237

Vad, J., Cleland, J., De Clippele, L. H., de Froe, E., Kazanidis, G., Blackbird, S., Van Oevelen, D., Head, E., Yashayaev, I., Kenchington, E., de Moura Neves, Edinger, E., Coté, D., B., and Roberts, J. M. 2025. Drivers of Coral and Sponge Community Composition and Size Structure Revealed with Cumulative Abundance Profiles. *Marine Ecology*, **46(5)**: e70030. https://doi.org/10.1111/maec.70030

Vanegas-Cantarero, M. M., Pennock, S., Bloise-Thomaz, T., Jeffrey, H., and Dickson, M. J. 2022. Beyond LCOE: A multi-criteria evaluation framework for offshore renewable energy projects. *Renewable and Sustainable Energy Reviews*, **161**: 112307. https://doi.org/10.1016/j.rser.2022.112307

Watling, L., and Auster, P. J. 2021. Vulnerable marine ecosystems, communities, and indicator species: confusing concepts for conservation of seamounts. *Frontiers in Marine Science*, **8**: 622586. https://doi.org/10.3389/fmars.2021.622586

Warawa, D., Curtis, J., Rooper, C., Nephin, J., Georgian, S., Chu, J. W. F., Dudas, S., and Knudby, A. 2025. Identification of Vulnerable Marine Ecosystems on Seamounts in the North Pacific Fisheries Commission Convention Area using Visual Surveys and Distribution Models. *DFO Can. Sci. Advis. Sec. Res. Doc.* **2025/014**. vi + 42 p. https://publications.gc.ca/site/archivee-archived.html?url=https://publications.gc.ca/collections/collection_2025/mpo-dfo/fs70-5/Fs70-5-2025-014-eng.pdf

Weiand, L., Unger, S., Rochette, J., Müller, A., and Neumann, B. 2021. Advancing ocean governance in marine regions through stakeholder dialogue processes. *Frontiers in Marine Science*, **8**: 645576. https://doi.org/10.3389/fmars.2021.645576

Williams, A. 2011. Bottom Fishery Impact Assessment Australian report for the South Pacific Regional Fisheries Management Organisation (SPRFMO). South Pacific Regional Fisheries Management Organisation. https://www.afma.gov.au/sites/default/files/2023-02/bottom_fishery_impact_assessment_sprfmo.pdf

Zhou, S., and Griffiths, S. P. 2008. Sustainability Assessment for Fishing Effects (SAFE): A new quantitative ecological risk assessment method and its application to elasmobranch bycatch in an Australian trawl fishery. *Fisheries Research*, **91(1)**: 56–68. https://doi.org/10.1016/j.fishres.2007.11.007

Zelli, E., Ellis, J., Pilditch, C., Rowden, A. A., Anderson, O. F., Geange, S. W., Bowden, D. A., and Stephenson, F. 2025. Identifying climate refugia for vulnerable marine ecosystem indicator taxa under future climate change scenarios. *Journal of Environmental Management*, **373**: 122635. https://doi.org/10.1016/j.jenvman.2024.122635

J. Northw. Atl. Fish. Sci., Vol. 57, Special Issue: 55–67
Conference article
Publication (Upload) date: 11 Sep. 2026

Quantifying and Communicating Uncertainty in Spatial Advice: A Practitioner's Guide

Neil Campbell
International Council for the Exploration of the Seas,
44-46 HC Andersens Boulevard, Copenhagen. Email: Neil.Campbell@ices.dk
Campbell, N. 2026. Quantifying and Communicating Uncertainty in Spatial Advice: A Practitioner's Guide. *J. Northw. Atl. Fish. Sci.*, **57(1)**: 55–67. https://doi.org/10.2960/J.v57.m755

Abstract

Proper communication of uncertainty in scientific advice is crucial, allowing decision-makers to weigh risks, consider alternative scenarios, and develop robust policies that recognise the boundaries of available evidence. When uncertainties are poorly communicated, policymakers take decisions based on incomplete information, potentially leading to unexpected outcomes and public loss of trust when predictions prove imprecise. The challenge of communicating scientific uncertainty to policymakers has become increasingly critical as marine conservation efforts expand into data-poor deep-sea environments. Deep-sea vulnerable marine ecosystems (VMEs) present unique challenges, with a very small portion of the deep seafloor visually observed, and critical knowledge gaps spanning taxonomic identification, ecosystem dynamics, and spatial distribution patterns. Recent adoption of methods which allow uncertainty quantification, coupled with policy integration mechanisms, offer promising pathways forward, though significant institutional and technical barriers persist in translating complex scientific uncertainties into actionable conservation advice.

This exploration of current frameworks and case studies reveals that effective reflection of uncertainty in policy requires fundamental changes in approach by both scientists and decision makers, away from traditional deterministic advice toward probabilistic, adaptive advisory and management frameworks that explicitly acknowledge knowledge limitations while maintaining scientific best practice. The synthesis of lessons from regional fisheries management organizations (RFMOs) and comparative deep-sea jurisdictions provides practical guidance for scientists and managers navigating the interface between deep-sea research and policy implementation.

Keywords: Uncertainty quantification, Precautionary approach, Vulnerable marine ecosystems (VMEs), Deep-sea fisheries management, Spatial conservation advice, Science-policy interface

Introduction

The established response to scientific uncertainty in advice is the precautionary approach, which mandates that a lack of full scientific certainty should not preclude the implementation of protective measures (United Nations, 1992). In fisheries management, this principle is highly operationalised through harvest control rules and advisory frameworks that systematically reduce levels of exploitation as estimates of stock size become more uncertain or fall below biological reference points (FAO, 1995). This link between uncertainty and management action is less established for spatial advice in the marine domain. Here, uncertainty pertains to the precise location, extent, and vulnerability of complex features like vulnerable marine ecosystems (VMEs) the distribution and nature of pressures acting upon them, and the uncertainty inherent in the trade-offs and consequences that management actions may entail (Auster *et al.,* 2011). This complexity suggests that spatial management frameworks would be better supported by communication and consideration of scientific advice that explicitly recognises the spatial distribution of uncertainty, rather than relying solely on point records, hard boundaries and deterministic maps, allowing managers to make risk-based decisions, by choosing an acceptable level of risk tolerance.

In the context of risk tolerance, Type 1 (erroneous rejection of a true hypothesis) and Type 2 (erroneous acceptance of a false hypothesis) errors represent fundamentally different conservation risks in relation to VMEs, with distinct policy implications (Neyman and Pearson, 1933). A Type 1 error represents a scenario where management actions unnecessarily restrict fishing activities, for instance establishing a closure to protect a predicted VME that does not actually exist, or applying protection measures based on outdated observations of communities that have since disappeared due to natural processes or unrecorded impacts. Conversely, a Type 2 error represents a failure to protect an actual VME, such as when sampling bias leads to VMEs being missed in unsampled regions, when detection methods fail to identify cryptic or less conspicuous VME indicator species, or when conservative definitional thresholds exclude moderately dense but still vulnerable aggregations from protection (van Denderen *et al.,* 2022). Whilst Type 1 errors impose economic costs on fishing industries and may undermine stakeholder confidence in scientific advice, Type 2 errors result in the irreversible loss of vulnerable deep-sea ecosystems that may require millennia to recover. This asymmetry in consequences fundamentally shapes how the precautionary approach is operationalised in deep-sea fisheries management, with most frameworks deliberately slanted towards accepting Type 1 errors to minimise the risk of Type 2 errors.

The treatment of scientific uncertainty in international fisheries management has evolved from a general principle to a specific, operational requirement. While foundational agreements like the UN Convention on the Law of the Sea (UNCLOS) established a general duty to protect the marine environment, subsequent instruments have become far more explicit. The 1995 UN Fish Stocks Agreement was a landmark, codifying the "precautionary approach" and making it a binding principle for managing fisheries. This concept was extended to spatial conservation through instruments such as UN General Assembly Resolution 61/105, which obligates states to protect deep-sea Vulnerable Marine Ecosystems (VMEs) where they are "known *or likely* to occur," demanding proactive management based on best available data (UNGA, 2006). This trend is most recently seen in the 2023 Biodiversity Beyond National Jurisdiction (BBNJ) Treaty, which enshrines the precautionary and ecosystem-based approaches as core obligations for the high seas, mandating the explicit consideration of uncertainty in environmental impact assessments (United Nations, 2023). High-level political commitments like Sustainable Development Goal 14 and the "30 by 30" conservation target of the Kunming-Montreal Global Biodiversity Framework further amplify this imperative. Achieving such ambitious goals requires states and regional organisations to act swiftly through precautionary designations in the face of incomplete scientific knowledge.

Despite these clear obligations and ambitious targets, recent analyses of Regional Fisheries Management Organisation (RFMO) impact assessments reveal critical gaps in uncertainty management (Kaikkonen *et al*., 2024). Heavy reliance on fishery-dependent data creates ambiguity in data sources and methods, with only a subset of assessments adequately addressing species distribution model and habitat suitability model uncertainties. Most evaluations consider only direct impacts of fishing gear on seafloor communities, and not cumulative impacts from climate change, resource extraction or other human activities.

This review aims to provide a comprehensive framework for understanding, communicating and working with uncertainty in deep-sea VME conservation advice. First, it systematically describes the main sources of uncertainty that must be identified and addressed in any scientific advice on VME protection, organising these within a Pressure-State-Response (PSR) framework to clarify how uncertainties propagate through the assessment process (OECD, 1993). Second, it examines recent methodological and technological advances in quantifying and communicating these uncertainties, including developments in ensemble modelling, probabilistic mapping approaches, and interactive visualisation platforms that enable more transparent uncertainty communication. Through this synthesis, the review then seeks to bridge the gap between theoretical uncertainty frameworks and their practical implementation in deep-sea fisheries governance, providing actionable guidance for scientists, managers, and institutions navigating the interface between incomplete knowledge and urgent conservation needs.

A Framework for Understanding VME Uncertainties

To effectively communicate scientific advice and subsequently protect deep-sea ecosystems through fisheries management decisions, it is necessary to deconstruct the multiple layers of uncertainty. The PSR framework provides one logical structure to categorise these knowledge gaps. In the context of VMEs, uncertainty in one component amplifies uncertainty in the others: imprecise knowledge of pressures (*e.g.*, fishing) makes it difficult to assess the true state of the ecosystem, which in turn impacts confidence in predictions of the ecosystem's response to management. This section systematically explores the key uncertainties within each component.

Pressure

Fishing Activity Detection and Spatial Representation: Fishing activity in many RFMO contexts is recorded through a combination of logbooks and Vessel Monitoring System (VMS) data, though not all fleets or fisheries operating within RFMO regulatory areas are subject to VMS requirements, limiting the spatial coverage and consistency of fishing activity records. Assessing fishing pressure on VMEs faces challenges in both detecting fishing activity and representing it spatially. VMS data typically records vessel positions, headings and speeds at intervals of one to two hours, requiring researchers to infer fishing activity based on speed thresholds that distinguish between fishing (typically 2–5 knots for bottom trawling) and steaming activities (Gerritsen and Lordan, 2011). These speed-based classifications introduce substantial uncertainty, as vessels may reduce speed for reasons unrelated to fishing, such as navigation around obstacles, weather conditions, or mechanical issues, whilst conversely, fishing may occur at atypical speeds depending on gear type, target species, or seabed conditions (Hintzen *et al*., 2012). This detection uncertainty is compounded by challenges in spatial representation, as the temporal resolution of VMS data limits the scale at which fishing activity can be accurately mapped. A VMS position report indicates that a vessel was present at a point in space and time but reveals nothing about where it travelled in the preceding and subsequent periods. The optimal scale for representing VMS-derived fishing activity is the product of average fishing speed and average interval between reports. Gridding at finer scales risks vessels fishing across grid cells without detection, underestimating impacts. Conversely, gridding at larger scales may create an erroneous perception of overlaps between fishing activity and actual VME locations (Amoroso *et al*., 2018). Moreover, this information indicates the vessel's position rather than the actual location where the fishing gear contacted the seafloor. In deep-sea fisheries, given a typical trawl warp length required is two to three times the water depth, the net may be operating several kilometres away from the vessel's recorded position.

Linking VMS Data to Gear Information: A limitation in VMS-based impact assessment stems from the difficulty of reliably linking vessel position data to information specifying the fishing gear being deployed. VMS data alone provides vessel location and speed but lacks details about gear type, size, or operational characteristics - information essential for calculating swept areas and impact intensities. This data integration challenge has significantly constrained spatial fishing advice, for example limiting the International Council for the Exploration of the Seas (ICES) ability to deliver comprehensive VME impact assessments to the North East Atlantic Fisheries Commission (NEAFC) in recent years (ICES, 2024). While the "ICES VMS & Logbooks data call" (ICES, 2026) attempts to standardise the linking of positional data with gear specifications, implementation remains inconsistent and coverage incomplete (ICES, 2025). The increasing use of Automatic Identification System (AIS) data has enabled large-scale analyses of apparent fishing activity, but these approaches face challenges in quantifying fishing activity and linking positional data to gear specifications, particularly in offshore areas (ICES, 2019; Hintzen *et al*., 2025). Whilst AIS-based studies can identify broad patterns of vessel activity and distinguish between mobile and static fishing operations, they cannot differentiate between specific gear types (*e.g.*, beam trawls versus seines), meaning that impact assessments may significantly misrepresent actual benthic disturbance compared to logbook-linked VMS data which provide precise gear-specific information.

Inferring Seafloor Disturbance: Translating vessel activity into benthic impact relies on multiple uncertain parameters that interact in complex ways. The actual impact of a trawl upon the seabed depends on gear-specific parameters like the effective width and weight of doors and ground gear, which vary with substrate, currents, and operational techniques (Clark *et al*., 2016). The spread of trawl gears is dynamically influenced by both the speed the gear is towed through the water, how the net has been rigged by the fisher, and the depth at which it is being fished (ICES, 2019). The choice of speed thresholds used to classify VMS pings as "fishing" versus "steaming" directly affects swept area calculations, as swept area is calculated as the product of gear width and fishing speed. If speed thresholds are set too low, non-fishing activities may be misclassified as fishing, inflating impact estimates; conversely, if thresholds are too high, actual fishing at slower speeds may be missed, leading to underestimation of cumulative impacts. This methodological choice thus introduces systematic bias into impact assessments, with the direction and magnitude of bias varying depending on fishery-specific operational practices and environmental conditions. Estimating bottom contact time from VMS tracks compounds these uncertainties, as it requires assumptions about when gear deployment begins and ends relative to vessel position records, creating additional layers of uncertainty.

Static Gears: Static fishing gears such as longlines, gillnets, and traps present unique challenges for VMS-based activity detection that are fundamentally different from mobile gears. The deployment and retrieval speeds of static gears often fall within the same range as normal steaming speeds, making it impossible to distinguish gear operations from transit using speed-based classifications alone. Combined with the coarse temporal resolution of VMS data (one- to two hour intervals), this means that while it may be possible to infer locations where gears have been retrieved, the actual deployment and duration of operations remain largely unobserved, in contrast to experiences with AIS data in small-scale fisheries (*e.g.* Mendo *et al*., 2023). This fundamental limitation prevents the derivation of "soak times" (the duration that gear remains fishing on the seabed) from VMS data, information that is required for assessing cumulative impact on benthic communities. The degree to which VME indicator species are vulnerable to damage from static gears is also variable and not well parameterised (Dias *et al*., 2020).

Historical and Cumulative Pressure: Assessing the cumulative impact of fishing over time presents additional methodological challenges that are particularly acute for deep-sea VME assessments. Reconstructions of historical fishing effort rely on incomplete and often spatially imprecise logbook data from previous decades, with data quality and spatial resolution declining markedly for earlier time periods (NAFO, 2009). High-seas fisheries that were once highly productive, for example the Grand Bank cod stocks that straddle the Canadian EEZ and Northwest Atlantic Fisheries Organisation (NAFO) regulatory area boundary, may have been under moratoria for decades, creating significant gaps in our understanding of historical fishing footprints. Areas that appear pristine in contemporary VMS data may have experienced intensive trawling historically. This temporal uncertainty means that current "baseline" conditions for many deep-sea areas may already reflect heavily degraded states, while areas with limited recent fishing activity may have experienced significant impacts that are absent from contemporary management assessments (Pitcher and Lam, 2010). The inability to account for this legacy of disturbance introduces systematic bias into impact assessments, potentially underestimating the true cumulative pressure on VME communities and overestimating their current resilience to additional fishing impacts.

A further source of historical uncertainty lies in the spatial precision of pre-VMS logbook records themselves. Prior to mandatory VMS implementation, fishing positions were typically recorded by skippers at the point of departure or return to port, or estimated from memory, rather than captured continuously during fishing operations. Where positions were recorded at sea, they were commonly rounded to the nearest degree or half-degree of latitude and longitude - a spatial imprecision of up to 55 km - rendering fine-scale reconstruction of historical fishing footprints impossible (Jennings and Lee, 2012). This positional uncertainty is particularly acute for deep-sea fisheries that expanded rapidly during the 1970s and 1980s, precisely the period for which establishing pre-disturbance baselines would be most valuable for contemporary assessments.

State

Characteristics of Vulnerable Marine Ecosystems: Although international guidelines for identifying VMEs have been established (FAO, 2009), their interpretation and implementation varies across organisations. Key definitional elements - what constitutes a VME, which taxa qualify as “VME indicators,” and required density thresholds to represent an “encounter” - are applied inconsistently between jurisdictions (Watling and Auster, 2021). Beyond habitat-forming organisms like corals and sponges, criteria such as “other locations that support species aggregations” remain poorly defined, with limited guidance for identifying features like seamount spawning aggregations or deep-sea nursery areas. The qualitative nature of many VME descriptors (*e.g.*, “significant concentrations,” “essential fish habitat”) introduces subjective interpretation that varies between scientists, institutions and regulatory frameworks, creating inconsistency in protection across regions.

Identifying and Sampling VMEs: The ability to find and characterise VMEs is fundamentally limited by the challenges of operating in the deep seas. With less than 0.001% of the deep seafloor visually observed, current knowledge is based on a tiny and highly biased sample. Data collection is concentrated in areas accessible to research vessels or within existing fishing grounds, meaning vast, unexplored regions are entirely absent from models and assessments (Clark *et al*., 2010). Survey methods themselves introduce systematic bias, with different techniques (cameras, trawls, multibeam sonar) detecting different VME components and size classes, while operational capabilities, funding constraints, and logistical limitations determine survey timing and locations rather than optimal sampling design, further biasing results. The expense and complexity of deep-sea operations mean that many potential VME areas are sampled only once, providing no information on temporal variability or the persistence of observed communities. Furthermore, at-sea observer coverage is typically low and non-randomly distributed, with observer deployment concentrated on larger vessels or specific fleets (Ewell *et al*., 2020), meaning that bycatch records of VME indicator species from commercial fishing operations are likely to underrepresent true encounter rates and should be interpreted with caution when used as evidence of VME distribution (Morato *et al*., 2018). Observational data from commercial trawls raises the question of whether the VME an indicator organism was collected from still exists, and precisely where along the trawl path it was encountered, as specimens cannot be linked to specific locations within the towed track (Auster *et al*., 2011).

Taxonomic and Compositional Uncertainty: When potential VMEs are observed, correctly identifying their components presents additional challenges. Identification from imagery is often uncertain, as morphologically similar species can have very different vulnerabilities and ecological roles (Althaus *et al*., 2009). However, many of the traits that confer vulnerability - slow growth, longevity, and structural fragility - are shared across higher taxonomic levels such as family or class, meaning that identification uncertainty at the species level does not always compromise the ability to recognise a VME indicator and apply appropriate protection (Watling and Auster, 2021). Without physical voucher specimens, which are rarely collected due to the destructive nature of sampling and the fragility of many VME organisms, there is a risk of misclassifying communities and misjudging their conservation status. Even with correct taxonomic identification, the ecological roles and vulnerabilities of many deep-sea species remain unknown, making it difficult to assess the functional significance of observed communities or predict their responses to disturbance. This functional uncertainty extends to community-level properties, where the ecosystem services provided by different VME assemblages, their resilience to impact, and their recovery potential are largely unknown.

Assessing ecosystem state: Even where VMEs are successfully identified and sampled, quantifying their ecological condition and detecting change over time presents additional layers of uncertainty. Establishing meaningful baselines is severely hampered by the paucity of historical observations, meaning that current VME assessments often lack a reference point against which to measure change (Pitcher and Lam, 2010, Rossberg *et al*., 2017). Where repeat surveys do exist, distinguishing genuine ecological change from natural variability in community composition, abundance, and distribution requires long time series that are rarely available for deep-sea systems. The absence of standardised monitoring protocols across surveys and institutions further compounds this problem, as differences in methodology between sampling events can introduce artefactual apparent change that is indistinguishable from real ecological trends. These limitations mean that assessments of ecosystem state are typically snapshots rather than trajectories, providing limited ability to detect gradual degradation or assess whether management measures are delivering ecological recovery. A particular challenge that is actively debated within RFMOs and approached differently across jurisdictions lies in determining whether a VME has been degraded to the point of Significant Adverse Impact. Defining thresholds for ecosystem state requires both empirical data on reference conditions and agreement on acceptable levels of depletion, neither of which is straightforward for deep-sea systems (Hiddink *et al.*, 2023a). The resolution of the habitat and fishing effort data used in state assessments further influences outcomes, with coarser data tending to obscure localised impacts and potentially underestimate the extent of degradation (Hiddink *et al.*, 2023b). Some RFMOs have developed quantitative approaches to assess ecosystem state with explicit uncertainty, such as the Relative Benthic Status (RBS) method applied within the South Pacific Regional Fisheries Management Organisation (SPRFMO) to estimate the current status of VME indicator taxa relative to an unfished baseline (SPRFMO, 2024).

Response

Assessing Vulnerability and Recovery Potential: Fundamental uncertainty exists regarding the intrinsic vulnerability of deep-sea species and communities to different disturbance types and intensities. Recovery timescales remain largely unknown for most VME taxa, with estimates spanning orders of magnitude from decades to millennia (Strong *et al*., 2023). This temporal uncertainty is compounded by ecological uncertainty about whether disturbed communities will follow predictable recovery pathways or shift to alternative stable states, and whether recovery trajectories observed in one location or environmental context can be reliably extrapolated to other sites or future conditions (Schlacher *et al*., 2010). These uncertainties limit managers' ability to make proportionate decisions about protection levels and duration, as it becomes difficult to weigh the costs of closures against conservation benefits or set appropriate review timelines.

Effort Displacement and Spatial Response: Management responses, particularly area closures, create cascading uncertainties about how fishing effort redistribution will affect marine ecosystems. The spatial distribution of displaced fishing activity cannot be predicted with certainty, as it depends on complex interactions between vessel economics, resource availability, regulatory frameworks, and fisher behaviour patterns that vary across fleets and seasons. This displacement uncertainty is coupled with ecological uncertainty about the vulnerability of receiving areas to newly concentrated fishing pressure, creating the potential for unintended consequences where protecting one VME can inadvertently lead to impacts on previously unfished areas (Auster *et al*., 2011; Lohrer *et al.,* 2023). These uncertainties undermine the effectiveness of spatial management tools by making it impossible to predict whether a closure will simply shift impacts to adjacent vulnerable areas, potentially creating a cycle of sequential habitat degradation. Managers cannot assess the true net conservation benefit of spatial closures, as positive effects in protected areas may be offset by negative effects in receiving areas, forcing them to choose between small, targeted closures, which may simply displace effort and be difficult to enforce, and larger, comprehensive closures, which may be economically and politically challenging.

Cumulative and Interactive Effects: Anticipating how VME communities will respond to multiple, interacting stressors operating across different spatial and temporal scales. Climate change, ocean acidification and direct fishing impacts interact in complex, non-linear ways that challenge current predictive capacity and introduce substantial uncertainty into any projections of combined effects. The cumulative effects of these stressors on VME resilience, recovery potential, and ecosystem functioning remain highly uncertain, particularly under projected future ocean conditions where baseline environmental parameters will fall outside the range of historical variability (Puerta *et al*., 2020). This uncertainty extends to the effectiveness of current management measures under changing environmental conditions and the potential for threshold effects or tipping points in ecosystem responses (Stephenson *et al*., 2023). These uncertainties make it extremely difficult for managers to set appropriate management targets or assess whether current measures are sufficient, as they cannot reliably predict how VMEs will respond to the combination of fishing pressure and climate change. These conditions force managers to make decisions with limited understanding of the relationship between management actions and ecological outcomes, significantly impeding evidence-based policy development and pushing advisory frameworks toward precautionary recommendations that stakeholders often perceive as excessively conservative.

The uncertainties described above do not exist in isolation but interact to create systematic biases in our ability to identify and protect VMEs, whilst simultaneously constraining the range of management options available to fisheries managers. An understanding of both the directional nature of these biases and their impact on advisory frameworks is necessary to develop and implement appropriate precautionary measures (Kenny *et al.,* 2018). Table 1 provides a systematic overview of the key uncertainty sources and their likely impact on conservation outcomes, categorised by whether they tend towards Type 1 errors (protection of areas where VMEs may not occur) or Type 2 errors (failure to protect actual VMEs). This analysis reveals a fundamental asymmetry: inherent scientific and observational limitations create a strong underlying tendency towards Type 2 errors, systematically causing us to underestimate VME presence and distribution. However, the management implications of these uncertainties extend beyond simple error classification and create a systematic bias toward highly precautionary approaches.

Quantifying and Visualising Uncertainty

Faced with the sources of uncertainty outlined above, the scientific community has worked to develop a suite of technical and methodological innovations that can better quantify, communicate, and manage these knowledge gaps. This represents a fundamental shift away from deterministic advice toward a risk-based approach that explicitly acknowledges uncertainty whilst maintaining scientific rigour.

Quantification of Pressure

To address the uncertainty around fishing effort estimation, researchers have moved beyond simple speed-filter methods toward probabilistic approaches. Hidden Markov Models (HMMs) now assign probability distributions to vessel "fishing states" based on sequences of positional data, incorporating speed, turning angle, and temporal patterns for more nuanced activity classification (Le Guyader *et al*., 2017). These models provide confidence intervals around fishing effort estimates rather than deterministic classifications.

For issues with identifying static gear deployments, technological solutions are emerging through direct gear instrumentation. Acoustic pingers, depth sensors, and GPS loggers deployed on longlines and trap arrays provide ground-truth data on gear deployment locations and soak times, enabling validation of VMS-based inferences (Sala *et al*., 2023). However, these approaches remain limited by cost, technical complexity, and the need for industry cooperation.

Physical trawl footprint models have evolved from fixed assumptions to parameterised, probabilistic approaches that incorporate gear-specific variables, substrate interactions, and environmental conditions. Monte Carlo simulations have been used to generate uncertainty distributions around swept area estimates, allowing impact assessments to express confidence intervals rather than point estimates (Eigaard *et al*., 2016).

Assessment of State

Quantitative assessments of ecosystem state increasingly draw on meta-analyses of empirical studies to derive estimates of VME indicator depletion and recovery potential, though the uncertainty inherent in extrapolating values from disparate study systems to specific management contexts remains substantial (Hiddink *et al*., 2023a; 2023b). In relation to mitigating VME identification and sampling uncertainties, ensemble species distribution modelling has become the standard approach for habitat suitability assessment. Such models combine outputs from multiple algorithms such as Boosted Regression Trees and Random Forest, alongside Bayesian approaches that use Integrated Nested Laplace Approximations (INLA) as an efficient method for estimating posterior distributions within spatial models, to generate both habitat suitability predictions and explicit uncertainty maps showing model agreement and confidence levels (Rubbens *et al*., 2023).

Machine learning applications, particularly Convolutional Neural Networks (CNNs), now enable semi-automated analysis of seafloor imagery with built-in confidence scoring. These systems achieve classification accuracies up to 80% whilst providing uncertainty estimates for each taxonomic identification, directly addressing the taxonomic uncertainty challenges outlined above (Zurowietz *et al*., 2018).

Environmental DNA (eDNA) techniques offer a promising approach to the spatial sampling limitations identified in the State framework. By detecting genetic material shed by VME indicator species, eDNA can screen vast areas more efficiently than traditional visual surveys, though it introduces new uncertainties around DNA transport and persistence in deep-sea environments (Gallego *et al*., 2024; Stefanni *et al*., 2022).

Visualisation and Communication

Advances in uncertainty quantification require effective communication tools to be operationally useful. Interactive decision support tools now allow managers to explore multi-layered uncertainty products, adjusting confidence thresholds and viewing how predictions change across different spatial scales (Rowden *et al*., 2019). These platforms can help distinguish between predicted VME likelihood and model confidence, enabling users to understand both the scientific prediction and the certainty associated with it.

Mapping techniques that simultaneously display both predicted habitat suitability and model uncertainty provide more nuanced information than simple presence/absence maps by showing the full range of scientific confidence. These bivariate visualisations help managers distinguish

Table 1. Sources of uncertainty in VME spatial advice and their error bias.

Source of Uncertainty	Description	Likely Error Bias
Data Collection and Observation		
Sampling Bias	VME data is collected non-randomly, concentrating on fished areas, seamounts, or along ship tracks, rather than being representative of the entire management area.	**Type 2.** Systematic failure to identify VMEs in extensive unsampled regions results in underestimated distributions and inadequate protection of undetected habitats.
Detection Probability	Survey methods have inherent biases. Cameras are good for large, erect fauna but often miss small, cryptic, or encrusting VME indicator species. Trawls only sample what they can catch.	**Type 2.** The presence and density of less-conspicuous VME indicator taxa are consistently underestimated, meaning areas that qualify for protection might be missed.
Taxonomic Uncertainty	Species are often identified from low-resolution imagery, making it difficult to distinguish between a vulnerable VME indicator and a morphologically similar, non-vulnerable species. However, as vulnerability traits such as slow growth and structural fragility are frequently shared across higher taxonomic levels, misidentification at species level does not always compromise VME recognition.	**Leans toward Type 2**, though the conservation consequence of taxonomic uncertainty is moderated where vulnerability is conserved at family or class level. The greater risk remains failing to recognise a true VME indicator where morphological similarity leads to misclassification as a non-vulnerable taxon.
Temporal Mismatch	Management advice is based on historical observations. A VME observed 30 years ago may no longer be present due to natural change or unrecorded fishing impacts.	**Type 1.** An area is protected based on a historical record of a VME that no longer exists, leading to an unnecessary restriction on human activities.
Modelling and Prediction		
Model Extrapolation	A habitat suitability model is applied to a new geographic region or to environmental conditions outside the range of the data it was trained on, where its predictive power is unknown.	**Both.** The model could dramatically overpredict suitable habitat (Type 1) or completely fail to identify suitable conditions because the ecological relationships are different (Type 2). This introduces high, but not directionally biased, error.
Predictor Variable Error	The environmental data layers used in models (e.g., bathymetry, substrate maps) have their own errors and are often at a coarse resolution that smooths over smaller VME habitats like pinnacles or canyons.	**Leans toward Type 2.** The smoothing effect of coarse environmental data is more likely to cause models to miss small, suitable habitat features than to create false ones, leading to an under-prediction of VME locations.
Definition and Application		
Definitional Ambiguity	The thresholds for what constitutes a "VME" (e.g., density of indicator species) are often qualitative or inconsistently applied, creating uncertainty about which observed aggregations qualify for protection.	A *conservative* definition (low threshold) intentionally invites **Type 1 errors** to be precautionary. A *permissive* definition (high threshold) leads to **Type 2 errors** by failing to protect moderately dense but still vulnerable areas.
Spatial Discretisation	The process of converting a continuous probability map from a model into a discrete polygon for a management closure. Boundaries are often simplified and buffered for practical enforcement.	**Type 1.** To ensure the high-probability core is protected and to create manageable boundaries, polygons are almost always drawn larger than the predicted VME footprint. This deliberately protects non-VME habitat, a precautionary Type 1 error.

between areas of high predicted suitability with low confidence (requiring additional research) and areas of moderate suitability with high confidence (suitable for immediate management action).

Evolving Policy and Management Frameworks

Whilst technical advances have improved uncertainty quantification and communication, they reveal a critical distinction between what can and cannot be solved through better methods. These solutions make uncertainties more explicit and manageable for decision-making, but they cannot eliminate the underlying knowledge gaps about VME distribution and vulnerability. The fundamental challenge of translating inherent scientific uncertainty into precautionary yet practical management policies remain. Resolving this requires institutional and policy innovation rather than purely technical solutions, representing a shift from asking “how certain are we?” to “how do we act responsibly given what we don’t know?”

These methodological advances enable scientists to provide advice with explicit confidence levels and probabilistic outcomes rather than deterministic statements. The question becomes: how should management frameworks respond to this more nuanced scientific input?

The value of uncertainty quantification tools depends on their integration into decision-making processes. This section examines how policy frameworks have evolved to incorporate explicit uncertainty into management actions. High-level agreements like the 2023 BBNJ Treaty have made precautionary and ecosystem-based approaches binding obligations, requiring explicit consideration of uncertainty in all management decisions.

The ICES approach exemplifies direct uncertainty communication in its VME assessment frameworks, combining habitat suitability predictions with confidence indices that separate scientific uncertainty assessment from management risk decisions (Morato *et al*., 2018; van Denderen *et al*., 2022). Different RFMOs have developed distinct approaches: CCAMLR uses precautionary encounter protocols where small VME bycatch (10 kg) triggers immediate local closures, effectively using fishing fleets as sampling tools (CCAMLR, 2024). SPRFMO relies on large model-based closures with higher encounter thresholds as backup protection (SPRFMO, 2022). GFCM has institutionalised uncertainty through adaptive management, establishing “Fisheries Restricted Areas” with regular review cycles that update rules based on new scientific information (GFCM, 2024). NAFO has developed a complementary suite of uncertainty communication tools within its VME assessment framework, using kernel density estimation (KDE) alongside species distribution models rather than relying on either approach alone (Kenchington *et al*., 2019). Model uncertainty is communicated explicitly through additional output layers, including the frequency of presence across cross-validation runs and the average probability of the dominant prediction class, providing managers with a direct visual representation of spatial confidence (Murillo *et al*., 2024, 2025; NAFO, 2024). Extrapolation areas, where models are applied beyond the environmental conditions of their training data, are also identified and mapped to flag predictions of unknown reliability (Mesgaran *et al*., 2014).

The diversity of these approaches reflects both the flexibility inherent in the precautionary principle and the genuine scientific uncertainty about which combination of encounter protocols, model-based closures, and adaptive review cycles best achieves VME protection in practice - a question that remains unresolved and argues for continued cross-RFMO learning and comparisons.

Roles of RFMOs and Advisory Bodies

The principles for effective communication require institutional support to be realised. Advisory bodies serve as the link between scientists, policymakers, and stakeholders, making them well-positioned to implement these approaches. Success requires three elements: maintaining technical consistency and quality, improving communication interfaces, and supporting adaptive governance.

Advisory bodies can foster common standards through several mechanisms: convening expert workshops to establish shared best practices for uncertainty quantification, providing clear guidance that requests explicit uncertainty assessments (using confidence indices or pedigree matrices), and commissioning comparative studies of different modelling approaches to build collective understanding of their strengths and weaknesses.

Advisory bodies act as “knowledge-brokers” between scientists and managers in policy systems (Pielke Jr, 2007). This exchange involves documenting all data, stakeholder input and scientific advice, including minority and dissenting views; facilitating structured discussions where policymakers can directly engage with scientific uncertainty; and developing communication tools, such as interactive formats that allow scientists and managers to explore risk scenarios together. For example, NAFO has developed an approach to bridge the science-policy gap through its Joint Commission-Scientific Council Working Group on Ecosystem Approach Framework to Fisheries Management (WG-EAFFM). This institutional mechanism demonstrates a practical way in which RFMOs can create structured opportunities for scientists and managers to address uncertainty in VME protection. The working group brings together fishery managers, scientists, and advisors from contracting parties in informal sessions where scientific advice can be explored before formal policy recommendations are developed.

The informal dialogue format used by WG-EAFFM effectively communicates spatial uncertainties in VME assessment and protection. During these sessions, scientists explain confidence intervals around habitat suitability models, discuss sampling bias in VME data, and describe directional biases. This transparency helps managers understand both what the science indicates and why precautionary measures are necessary given asymmetric risks. Since its inception in 2012, the working group has developed capacity to handle increasingly complex uncertainty frameworks, moving from basic vulnerability assessments to comprehensive treatments of encounter protocols, model extrapolation risks, and adaptive management cycles that acknowledge the provisional nature of spatial protection measures.

WG-EAFFM's structure recognises that effective uncertainty communication requires both technical translation and policy development. When discussions move from informal sessions to formal recommendations, the Scientific Council maintains representation whilst scientists remain within their national delegations. This structure preserves the understanding developed during informal exchanges when developing policy recommendations for the Commission. The working group's success in advancing VME protection measures how institutional mechanisms can translate complex scientific uncertainties into conservation policies that acknowledge their limitations whilst maintaining precautionary effectiveness. However, the NAFO WG-EAFFM model is not universally replicated across RFMOs, and many bodies lack equivalent fora for informal science-policy dialogue. Where such mechanisms do exist in other organisations - for example, the South Pacific Working Group (SPACWG) within SPRFMO, which brings together managers, scientists, fishing bodies, and environmental NGOs to discuss science feeding into the Scientific Committee - they fulfil a similar bridging function. In organisations where no such intermediate forum exists and scientific advice moves directly to formal deliberation, the nuances of uncertainty are less likely to be understood and incorporated into management decisions, representing a governance gap that warrants attention.

A Practitioner's Guide to Spatial Uncertainty

Table 2 translates the principles discussed in this review into practical recommendations for scientists, managers, and institutions working at the science-policy interface.

Conclusions

Scientific and observational limitations in the deep seas create a strong tendency towards Type 2 errors – a failure to protect VMEs. Precautionary advisory frameworks and management actions counter this underestimation by introducing Type 1 errors as a risk-averse strategy to ensure conservation goals are met. While states and RFMOs operate under the precautionary approach, they have implemented it differently for VME protection, ranging from highly risk-averse encounter protocols to large-scale predictive models to adaptive management cycles.

Uncertainty communication in deep-sea VME conservation represents one of the most challenging interfaces between marine science and policy. Extreme data limitations, technological constraints, and institutional complexity create advisory challenges that exceed those in other marine systems. Success requires shifts from deterministic advice toward probabilistic, adaptive frameworks that acknowledge knowledge limitations whilst maintaining scientific credibility. Effective approaches combine sophisticated uncertainty quantification with clear communication strategies, precautionary policy frameworks, and stakeholder engagement that acknowledges both scientific and value uncertainties.

These challenges extend beyond deep-sea conservation into virtually all domains where scientific advice informs spatial decision-making. The Pressure-State-Response uncertainty framework applies equally to offshore renewable energy development, marine spatial planning, and coastal management. VME protection is distinguished not by the nature of these uncertainties, but by extreme data limitations and irreversibility of impacts that make precautionary approaches particularly critical.

The communication strategies, stakeholder engagement principles, and adaptive management frameworks outlined here provide transferable guidance for any spatial advice context where scientific uncertainty must be translated into policy decisions. Success will depend on continued investment in methodological development, capacity building across the science-policy interface, and institutional innovations that embrace uncertainty as inherent to complex marine systems rather than as a barrier to conservation action. The challenge is not to eliminate uncertainty, but to communicate and manage it effectively.

Acknowledgements

The author thanks the two anonymous reviewers for their careful and constructive comments, which substantially improved the manuscript. Thanks are also due to the editor, for her patience in coordinating the review process. The views expressed in this paper are the personal opinions of the author alone and do not represent any institutional position.

Table 2. Recommendations for scientists, managers, and institutions working with uncertainty at the science-policy interface.

Scientists: Communicating Uncertainty Effectively	
Principle	**Action**
Quantify Uncertainty	Move beyond stating that 'more research is needed' by quantifying and presenting uncertainty explicitly across all components of the assessment. For pressure, this means expressing fishing effort and swept area estimates with confidence intervals derived from probabilistic approaches such as Hidden Markov Models or Monte Carlo simulations, rather than deterministic classifications. For state, uncertainty can be communicated through ensemble modelling, Bayesian approaches, cross-validation outputs, or other methods appropriate to the data and context, generating uncertainty maps alongside habitat suitability predictions and presenting results with confidence intervals rather than point estimates.
Visualise the Unknown	Maps showing what is not known can be as valuable as maps showing what is predicted. Use bivariate maps to display both VME likelihood and model confidence, and interactive platforms that allow managers to explore how different risk thresholds affect management options.
Be Explicit About Bias	Clearly explain directional biases in your data and methods, and if sampling limitations mean your assessment is more likely to miss VMEs, state this directly by including a summary table in advisory notes that explains each major uncertainty source and its likely effect on conservation outcomes.
Use Structured Frameworks	Organise advice using logical frameworks like Pressure-State-Response to break complex problems into understandable components by structuring assessment reports around the PSR framework and linking fishing pressure uncertainties to ecosystem state uncertainties and response uncertainties.
Managers and Policymakers: Operating Under Uncertainty	
Request Better Advice	Do not accept deterministic advice without uncertainty information. When setting terms of reference for scientific advice, explicitly request uncertainty quantification such as confidence maps, probability scores, and risk scenarios. The NAFO WG-EAFFM model provides a practical example, where informal dialogue sessions are structured specifically to allow managers to interrogate the uncertainty behind scientific advice before formal recommendations are developed.
Embrace Risk-Based Frameworks	Focus on choosing acceptable risk levels rather than seeking single "correct" answers by adopting management frameworks that allow explicit risk tolerance selection, such as protecting all areas with >60% chance of being a VME whilst acknowledging associated uncertainties.
Institutionalise Adaptability	Treat management measures as experiments to learn from rather than permanent solutions by building mandatory review cycles (every 3-5 years) into text of area closures and spatial measures, creating formal processes for incorporating new data and adapting management as uncertainty reduces.
Create Spaces for Dialogue	Effective policies benefit from co-development through informal discussion between scientists and managers before formal decisions, so support joint working groups like the NAFO WG-EAFFM model that bring scientists, managers, and stakeholders together to explore scientific advice nuances.
Institutions: Building capacity for effective science-policy communication	
Standardise	Ensure the processes behind the advice are transparent and repeatable, without prescribing specific scientific methods. Establish and adopt common standards for uncertainty reporting in scientific advice, such as requiring confidence indices.
Document	Ensure information flows freely and is well-documented by transparently recording and presenting all scientific input, including minority opinions and dissenting views, and developing and maintaining interactive data and advice portals.
Invest in the Interface	Dedicate resources to tools and people that facilitate communication by funding development of visualisation platforms and decision-support tools and supporting workshops and training that build communication capacity for scientists and uncertainty interpretation skills for managers.
Formalise	Translate high-level principles into clear operational rules for action under uncertainty by developing clear encounter protocols, model-based frameworks, and adaptive management cycles that provide precautionary pathways for decision-making when data is limited.

References

Althaus, F., Williams, A., Schlacher, T. A., Kloser, R. J., Green, M. A., Barker, B. A., Bax, N. J., Brodie, P. and Schlacher-Hoenlinger, M. A. 2009. Impacts of bottom trawling on deep-coral ecosystems of seamounts are long-lasting. *Marine Ecology Progress Series*, **397**: 279–294. https://doi.org/10.3354/meps08248

Amoroso, R. O., Pitcher, C. R., Rijnsdorp, A. D., McConnaughey, R. A., Parma, A. M., Suuronen, P., Eigaard, O. R., Bastardie, F., Hintzen, N. T., Althaus, F., Baird, S. J., Black, J., Buhl-Mortensen, L., Campbell, A. B., Catarino, R., Collie, J., Cowan, J. H., Durholtz, D., Engstrom, N., Fairweather, P., Fock, H. O., Ford, R., Gálvez, P. A., Gerritsen, H., Góngora, M. E., González, J. A., Hiddink, J. G., Hughes, K. M., Intelmann, S. S., Jenkins, C., Jonsson, P., Kainge, P., Kangas, M., Kathena, J. N., Kavadas, S., Leslie, R. W., Lewis, S. G., Lundy, M., Makin, D., Martin, J., Mazor, T., Gonzalez-Mirelis, G., Newman, S. J., Papadopoulou, N., Posen, P. E., Rochester, W., Russo, T., Sala, A., Semmens, J. M., Silva, C., Tsolos, A., Vanelslander, B., Wakefield, C. B., Wood, B. A., Hilborn, R., Kaiser, M. J., and Jennings, S. 2018. Bottom trawl fishing footprints on the world's continental shelves. *Proceedings of the National Academy of Sciences*, **115(43)**: E10275-E10282. https://doi.org/10.1073/pnas.1802379115

Auster, P. J., Gjerde, K., Heupel, E., Watling, L., Grehan, A., and Rogers, A. D. 2011. Definition and detection of vulnerable marine ecosystems on the high seas: problems with the "move-on" rule. *ICES Journal of Marine Science*, **68(2)**: 254–264. https://doi.org/10.1093/icesjms/fsq074

CCAMLR (Commission for the Conservation of Antarctic Marine Living Resources). 2024. Vulnerable Marine Ecosystems (VMEs). Retrieved from https://www.ccamlr.org/en/compliance/vulnerable-marine-ecosystems-vmes

Clark, M. R., Althaus, F., Schlacher, T. A., Williams, A., Bowden, D. A., and Rowden, A. A. 2016. The impacts of deep-sea fisheries on benthic communities: a review. *ICES Journal of Marine Science*, **73(suppl_1)**: i51–i69. https://doi.org/10.1093/icesjms/fsv123

Clark, M. R., Consalvey, M., and Rowden, A. A. 2010. *Biological sampling in the deep sea*. John Wiley & Sons.

Dias, V., Oliveira, F., Boavida, J., Serrão, E. A., Gonçalves, J. M. and Coelho, M. A., 2020. High coral bycatch in bottom-set gillnet coastal fisheries reveals rich coral habitats in southern Portugal. *Frontiers in Marine Science*, **7**: 603438. https://doi.org/10.3389/fmars.2020.603438

Eigaard, O. R., Bastardie, F., Breen, M., Dinesen, G. E., Hintzen, N. T., Laffargue, P., Mortensen, L. O., Nielsen, J. R., Nilsson, H. C., O'Neill, F. G. and Polet, H. 2016. Estimating seabed pressure from demersal trawls, seines, and dredges based on gear design and dimensions. *ICES Journal of Marine Science*, **73(suppl_1)**: i27–i43. https://doi.org/10.1093/icesjms/fsv099

Ewell, C., Hocevar, J., Mitchell, E., Snowden, S. and Jacquet, J., 2020. An evaluation of Regional Fisheries Management Organization at-sea compliance monitoring and observer programs. *Marine Policy*, **115**: 103842. https://doi.org/10.1016/j.marpol.2020.103842

FAO. 1995. Reference Points for Fisheries Management. *FAO Fisheries Technical Paper* No. 347. Rome, FAO. 83 p. https://www.fao.org/4/v8400e/V8400E02.HTM

FAO. 2009. International Guidelines for the Management of Deep-sea Fisheries in the High Seas. UN Food and Agriculture Organization, Rome. 90 p.

Gallego, R., Arias, M. B., Corral-Lou, A., Díez-Vives, C., Neave, E. F., Wang, C., Cárdenas, P., Steffen, K., Taboada, S., Villamor, A., Kenchington, E., Mariani, S., and Riesgo, A. 2024. North Atlantic deep-sea benthic biodiversity unveiled through sponge natural sampler DNA. *Commun. Biol.* **7**, 1015. https://doi.org/10.1038/s42003-024-06695-4

Gerritsen, H., and Lordan, C. 2011. Integrating vessel monitoring systems (VMS) data with daily catch data from logbooks to explore the spatial distribution of catch and effort at high resolution, *ICES Journal of Marine Science*, **Volume 68**, **Issue 1**: January 2011, 245–252. https://doi.org/10.1093/icesjms/fsq137

GFCM (General Fisheries Commission for the Mediterranean). 2024. Fisheries restricted areas and how the GFCM contributes to biodiversity conservation. Retrieved from https://www.fao.org/gfcm/news/detail/en/c/1733981/

Hiddink, J. G., Valanko, S., Delargy, A. J., and van Denderen, P. D. 2023a. Setting thresholds for good ecosystem state in marine seabed systems and beyond. *ICES Journal of Marine Science*, **80**: 698–709. https://doi.org/10.1093/icesjms/fsad035

Hiddink J. G., Evans, L., Gilmour, F., Lourenço, G., McLennan, S., Quinn, E., and Shepperson, J. 2023b. The effect of habitat and fishing-effort data resolution on the outcome of seabed status assessment in bottom trawl fisheries. *Fisheries Research*, **259**: 106578. https://doi.org/10.1016/j.fishres.2022.106578

Hintzen, N. T., Bastardie, F., Beare, D., Piet, G. J., Ulrich, C., Deporte, N., Egekvist, J., and Degel, H., 2012. VMStools: open-source software for the processing, analysis and visualisation of fisheries logbook and VMS data. *Fisheries Research*, **115**: 31–43. https://doi.org/10.1016/j.fishres.2011.11.007

Hintzen, N. T., Brigden, K., Kaastra, H. J., Mackinson, S., Pastoors, M. A., and Van de Pol, L., 2025. Bias in Global Fishing Watch AIS data analyses results in overestimate of Northeast Atlantic pelagic fishing impact. *ICES Journal of Marine Science*, **82(3)**: fsaf033. https://doi.org/10.1093/icesjms/fsaf033

NAFO. 2009. Delineation of Existing Bottom Fishing Areas in the NAFO Regulatory Area. *NAFO/FC Doc.* **09/20**, Serial No. N5712: 10 p. https://www.nafo.int/Portals/0/PDFs/fc/2009/fcdoc09-20.pdf

ICES. 2019. Working Group on Spatial Fisheries Data (WGSFD). *ICES Scientific Reports*. **1(52):** 144 p. https://doi.org/10.17895/ices.pub.5648

ICES. 2024. NEAFC request on vulnerable marine ecosystems in the NEAFC Regulatory Areas, in relation to the NEAFC 5-year review of Recommendation 19:2014. *In*: Report of the ICES Advisory Committee, 2024. ICES Advice 2024, sr.2024.15. https://doi.org/10.17895/ices.advice.27101119

ICES. 2025. Working Group on Spatial Fisheries Data (WGSFD; outputs from 2024 meeting). *ICES Scientific Reports*: **7:81**.

96 p. https://doi.org/10.17895/ices.pub.30501452

ICES. 2026. Data call: VMS/Log book data for fishing activities in the Northeast Atlantic and Baltic Sea for the provision of ICES advice on the spatial distribution and impact of fisheries from 2009 to 2025. https://doi.org/10.17895/ices.pub.31554937

Jennings, S., and Lee, J. 2012. Defining fishing grounds with vessel monitoring system data. *ICES Journal of Marine Science*, **69(1)**: 51–63. https://doi.org/10.1093/icesjms/fsr173

Kaikkonen, L., Amaro, T., Auster, P. J., Bailey, D. M., Bell, J. B., Brandt, A., Clark, M. R., Drazen, J. C., Du Preez, C., Escobar-Briones, E. Giacomello, E., Gianni, M. Johnson, J. F. Levin, L. A., Milligan, R. J., Oduware, S., Pearman, T. R. R., Pham, C. K., Ramalho, S. P., Rowden, A. A., Sutton, T. T., Taylor, M. L. Watling, L., and Victorero, L. 2024. Improving impact assessments to reduce impacts of deep-sea fisheries on vulnerable marine ecosystems. *Marine Policy*, **167**, 106281. https://doi.org/10.1016/j.marpol.2024.106281

Kenchington, E., Lirette, C., Murillo, F. J., Beazley, L., and Downie, A. L., 2019. Vulnerable Marine Ecosystems in the NAFO Regulatory Area: Updated Kernel Density Analyses of Vulnerable Marine Ecosystem Indicators. *NAFO SCR Doc.* 19/058, Serial No. N7030, 68 p. https://www.nafo.int/Portals/0/PDFs/sc/2019/scr19-058.pdf

Kenny, A. J., Campbell, N., Koen-Alonso, M., Pepin, P. and Diz, D. 2018. Delivering sustainable fisheries through adoption of a risk-based framework as part of an ecosystem approach to fisheries management. *Marine Policy*, **93**: 232–240. https://doi.org/10.1016/j.marpol.2017.05.018

Le Guyader, D., Ray, C., Gourmelon, F., and Brosset, D. 2017. Defining high-resolution dredge fishing grounds with Automatic Identification System (AIS) data. *Aquatic Living Resources*, **30**, 39. https://doi.org/10.1051/alr/2017038

Lohrer, T., Hewitt, J. E., Lohrer, A. M., Parsons, D. M., Ellis, J. I., and Stephenson, F. 2023. Evidence of rebound effect in New Zealand MPAs: Unintended consequences of spatial management measures. *Ocean and Coastal Management*, **239**: 106595. https://doi.org/10.1016/j.ocecoaman.2023.106595

Mendo, T., Glemarec, G., Mendo, J., Hjorleifsson, E., Smout, S., Northridge, S., Rodriguez, J., Mujal-Colilles, A., and James, M. 2023. Estimating fishing effort from highly resolved geospatial data: Focusing on passive gears. *Ecological Indicators*, **154**: 110822. https://doi.org/10.1016/j.ecolind.2023.110822

Mesgaran, M. B., Cousens, R. D., and Webber, B. L. 2014. Here be dragons: a tool for quantifying novelty due to covariate and correlation change when projecting species distribution models. *Diversity and Distributions*, **20**: 1147–1159. https://doi.org/10.1111/ddi.12209

Morato, T., Pham, C.K., Pinto, C., Golding, N., Ardron, J. A., Duran Munoz, P., and Neat, F., 2018. A multi criteria assessment method for identifying Vulnerable Marine Ecosystems in the North-East Atlantic. *Frontiers in Marine Science*, **5**: 460 p. https://doi.org/10.3389/fmars.2018.00460

Murillo, F. J., Downie, A.-L., Abalo Morla, S., Lirette, C., Paulin, N., Wang, Z., Devred, E., Clay, S., Sacau, M., Nozères, C., Koen-Alonso, M., Gullage, L., and Kenchington, E. 2024. Vulnerable marine ecosystems in the Regulatory Area: updated species distribution models of selected vulnerable marine ecosystem indicators (large-sized sponges, sea pens and black corals). *NAFO SCR Doc.* **24/063,** Serial No. N7601: 105 p. https://www.nafo.int/Portals/0/PDFs/sc/2024/scr24-063.pdf

Murillo, F. J., Abalo Morla, S., Downie, A.-L., Lirette, C., Paulin, N., Wang, Z., Devred, E., Clay, S., Sacau, M., Nozères, C., Koen-Alonso, M., Gullage, L., Hayes, V., Caetano, M., Gonçalves, P., and Kenchington, E. 2025. Vulnerable Marine Ecosystems in the NAFO Regulatory Area: Updated Species Distribution Models of Selected Vulnerable Marine Ecosystem Indicators (Large and Small Gorgonian Corals, Erect Bryozoans and Sea Squirts). *NAFO SCR Doc.* **25/035**, Serial No. N7663: 62 p. https://www.nafo.int/Portals/0/PDFs/sc/2025/scr25-035REV.pdf

NAFO. 2024. Report of the 17th Meeting of the NAFO SC Working Group on Ecosystem Science and Assessment (WGESA) – November 2024. *NAFO SCS Doc.* **24/20**, Serial No. N7604. 101 p. https://www.nafo.int/Portals/0/PDFs/sc/2024/scs24-20.pdf

Neyman, J., and Pearson, E. S. 1933. On the problem of the most efficient tests of statistical hypotheses. P*hilosophical Transactions of the Royal Society of London*, S**eries A 231**: 289–337. https://doi.org/10.1098/rsta.1933.0009

OECD. 1993. OECD core set of indicators for environmental performance reviews: A synthesis report by the Group on the State of the Environment. Paris: OECD. (*Environment Monographs*, **No. 83**: OCDE/GD(93)179). https://one.oecd.org/document/OCDE/GD(93)179/En/pdf

Pielke Jr, R. A. 2007. *The honest broker: Making sense of science in policy and politics*. Cambridge University Press.

Pitcher, T. J., and Lam, M. E. 2010. Fishful thinking: rhetoric, reality, and the sea before us. *Ecology and Society*, **15(2)**: 12 p. https://doi.org/10.5751/ES-03320-150212

Puerta, P., Johnson, C., Carreiro-Silva, M., Henry, L.-A., Kenchington, E., Morato, T., Kazanidis, G., Rueda, J. L., Urra, J., Ross, S., Wei, C.-L., González-Irusta, J. M., Arnaud-Haond, S., and Orejas, C. 2020. Influence of water masses on the biodiversity and biogeography of deep-sea benthic ecosystems in the North Atlantic. *Frontiers in Marine Science*, **7**: 239 p. https://doi.org/10.3389/fmars.2020.00239

Rowden, A. A., Stephenson, F., Clark, M. R., Anderson, O. F., Guinotte, J. M., Baird, S. J., Roux, M.-J., Wadhwa, S., Cryer, M., and Lundquist, C. J. 2019. Examining the utility of a decision-support tool to develop spatial management options for the protection of vulnerable marine ecosystems on the high seas around New Zealand. *Ocean and Coastal Management*, **170**: 1–16. http://doi.org/10.1016/j.ocecoaman.2018.12.033

Rossberg, A. G., Uusitalo, L., Berg, T., Zaiko, A., Chenuil, A., Uyarra, M.C., Borja, A., and Lynam, C. P., 2017. Quantitative criteria for choosing targets and indicators for sustainable use of ecosystems. *Ecological Indicators*,

72, 215–224. https://doi.org/10.1016/j.ecolind.2016.08.005

Rubbens, P., Brodie, S., Cordier, T., Destro Barcellos, D., Devos, P., Fernandes-Salvador, J. A., Fincham, J. I., Gomes, A., Handegard, N. O., Howell, K., and Jamet, C. 2023. Machine learning in marine ecology: an overview of techniques and applications. *ICES Journal of Marine Science*, **80(7)**: 1829–1853. https://doi.org/10.1093/icesjms/fsad100

Sala, A., Depestele, J., Gümüş, A., Laffargue, P., Nielsen, J. R., Polet, H., Smith, C. J., Zengin, M., Bastardie, F., Eigaard, O. R., and Hamon, K. G., 2023. Technological innovations to reduce the impact of bottom gears on the seabed. *Marine Policy*, **157**: 105861. https://doi.org/10.1016/j.marpol.2023.105861

Schlacher, T. A., Williams, A., Althaus, F., and Schlacher-Hoenlinger, M. A. 2010. High-resolution seabed imagery as a tool for biodiversity conservation planning on continental margins. *Marine Ecology*, **31(1)**: 200–221. https://doi.org/10.1111/j.1439-0485.2009.00286.x

SPRFMO. 2022. Conservation and Management Measure for the Management of Bottom Fishing in the SPRFMO Convention Area (CMM 03-2022). Retrieved from https://www.sprfmo.int/

SPRFMO. 2024. Updated quantitative benthic impact assessment for New Zealand and Australian bottom fisheries. 12th Meeting of the SPRFMO Scientific Committee, 30 September – 5 October 2024, Lima, Peru. https://sprfmo.int/assets/Meetings/02-SC/12th-SC-2024/Deepwater/SC12-DW12-NZL-Updated-quantitative-benthic-impact-assessment-for-New-Zealand-and-Australian-bottom-fisheries.pdf

Stefanni, S., Mirimin, L., Stanković, D., Chatzievangelou, D., Bongiorni, L., Marini, S., Modica, M. V., Manea, E., Bonofiglio, F., del Rio Fernandez, J., Cukrov, N. Gavrilović, A., De Leo, F. C., and Aguzzi, J. 2022. Framing cutting-edge integrative deep-sea biodiversity monitoring via environmental DNA and optoacoustic augmented infrastructures. *Frontiers in Marine Science*, **8**: p.797140. https://doi.org/10.3389/fmars.2021.797140

Stephenson, F., Rowden, A. A., Anderson, O. F., Ellis, J., Geange, S., Brough, T., Behrens, E., Hewitt, J., Clark, M., Tracey, D., Goode, S. L., Petersen, G .L., and Lundquist, C. 2023. Implications for the conservation of deep-water corals in the face of multiple stressors: A case study from the New Zealand region. *Journal of Environmental Management*, **346**: 118938. https://doi.org/10.1016/j.jenvman.2023.118938

Strong, J. A., Piechaud, N., De Clippele, L. H., Bett, B. J., Horton, T., Corbera, G., and Huvenne, V. A., 2023. Recovery and restoration potential of cold-water corals: experience from a deep-sea marine protected area. *Restoration Ecology*, **31(8)**: e13970. https://doi.org/10.1111/rec.13970

UNGA (United Nations General Assembly). 2006. Resolution 61/105 on Sustainable fisheries, including through the 1995 Agreement for the Implementation of the Provisions of the United Nations Convention on the Law of the Sea of 10 December 1982 relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks, and related instruments. A/RES/61/105.

United Nations. 1992. Rio Declaration on Environment and Development, in the Report of the United Nations Conference on Environment and Development, UN Doc. A/CONF. 151/26 (**Vol. 1**), 12 August 1992. https://docs.un.org/en/A/CONF.151/26/Rev.1(vol.I)

United Nations. 2023. Agreement under the United Nations Convention on the Law of the Sea on the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction (BBNJ Agreement). Retrieved from https://www.un.org/bbnj/

Watling, L., and Auster, P. J. 2021. Vulnerable marine ecosystems, communities, and indicator species: confusing concepts for conservation of seamounts. *Frontiers in Marine Science*, **8**: 622586. https://doi.org/10.3389/fmars.2021.622586

van Denderen, P. D., Holah, H., Robson, L. M., Hiddink, J. G., Menot, L., Pedreschi, D., Kazanidis, G., Llope, M., Turner, P. J., Stirling, D., Murillo, F. J., Kenny, A., Campbell, N., Allcock, A. L., Braga-Henriques, A., González-Irusta, J. M., Johnston, G., Orejas, C., Serrano, A., Xavier, J. R., Hopkins, P., Kenchington, E., Nixon, E., and Valanko, S. 2022. A policy-based framework for the determination of management options to protect vulnerable marine ecosystems under the EU deep-sea access regulations. *ICES Journal of Marine Science*, **79(1)**, 34–49. https://doi.org/10.1093/icesjms/fsab237

Zurowietz, M., Langenkämper, D., Hosking, B., Ruhl, H. A., and Nattkemper, T. W. 2018. MAIA-A machine learning assisted image annotation method for environmental monitoring and exploration. *PloS one*, **13(11)**, e0207498. https://doi.org/10.1371/journal.pone.0207498

J. Northw. Atl. Fish. Sci., Vol. 57, Special Issue: 69–77 Publication (Upload) date: 11 Sep. 2026
Conference article

From Principle to Practice: A Pragmatic Pathway for Ecosystem-Based Fisheries Management in a Data-limited RFMO

Marco Milardi
Affiliation: Southern Indian Ocean Fisheries Agreement (SIOFA), 13 Rue de Marseille, 97420 Le Port, La Réunion.

Milardi, M. 2026. From Principle to Practice: a pragmatic pathway for Ecosystem-Based Fisheries Management in a data-limited RFMO. *J. Northw. Atl. Fish. Sci.*, **57(1)**: 69–77. https://doi.org/10.2960/J.v57.m756

Abstract

The Southern Indian Ocean Fisheries Agreement (SIOFA) is legally mandated through its founding agreement to implement an Ecosystem Approach to Fisheries Management (EAFM). However, like many Regional Fisheries Management Organizations (RFMOs), translating this principle into effective practice poses significant challenges, particularly in data-limited environments. This viewpoint paper traces SIOFA's pragmatic journey in operationalizing EAFM. We detail the organization's early adaptive strategies, which included precautionary alignment with other RFMOs for managing seabirds and Vulnerable Marine Ecosystems (VMEs), and evidence-based conservation measures for deepwater sharks driven by targeted ecological risk assessments. While effective, these approaches highlighted a fundamental barrier: the Scientific Committee's limited access to integrated fisheries data. In response, SIOFA developed an internal synthesis tool—the SIOFA Ecosystem Summary, to synthesize and streamline data access, thereby directly supporting science-based advice. This perspective paper argues that SIOFA's experience demonstrates a pragmatic, phased pathway for EAFM implementation that reflects broader trends among RFMOs. While similar ecosystem synthesis tools exist in other bodies (*e.g.*, NAFO, ICES, IOTC), SIOFA's process is distinctive in its iterative co-development between the Secretariat and Scientific Committee within a resource-constrained setting. This paper contends that such adaptive, context-sensitive approaches offer practical insights for data-limited RFMOs seeking to operationalize EAFM.

Keywords: Adaptive Management; Fisheries Governance; Precautionary Approach; Science-Policy Interface; SIOFA

Introduction

The Ecosystem Approach to Fisheries Management (EAFM, FAO, 2003) has emerged as a cornerstone of modern international fisheries governance, advocating for a holistic strategy that moves beyond a single-species focus to consider the entire ecosystem—including target and non-target species, habitats, and human communities—and thereby seeks to balance ecological, economic, and social objectives for long-term sustainability. While the principle is widely endorsed, its practical implementation by Regional Fisheries Management Organizations (RFMOs) remains a significant and complex challenge (Ramirez-Monsalve *et al.,* 2016), especially in data-limited contexts and for newer RFMOs (*i.e.*, established after the early 2000s) that need to build their management frameworks from the ground up (Fletcher, 2020).

The journey from the high-level principle of EAFM to its tangible, effective practice requires pragmatic solutions, institutional learning, and adaptive strategies (see *e.g.*, Fletcher *et al.,* 2010). This transition is fraught with operational hurdles, including reconciling short-term economic interests with long-term sustainability, managing uncertainties, and building the institutional capacity for complex systems thinking (*e.g.*, Fletcher, 2008). These challenges resonate strongly with concepts in the literature on adaptive management, which emphasizes iterative learning and flexible decision-making in the face of uncertainty (*e.g.*, Walters, 1986; Holling, 1978; Plagányi *et al.,* 2014; Fletcher and Bianchi*,* 2014). It is within this global context that the experience of the Southern Indian Ocean Fisheries Agreement (SIOFA) offers a valuable case study in applied adaptive management.

Established in 2012, but active starting from 2016, SIOFA is a relatively young RFMO that embodies this challenge, governing a vast and ecologically-significant area (Fig. 1). Comprising 10 Contracting Parties, one Participating Fishing Entity, and two Cooperating Non-Contracting Parties, SIOFA's core objectives are to ensure the long-term conservation and sustainable use of non-highly-migratory fishery resources in the high-seas of the agreement area, and to promote their sustainable

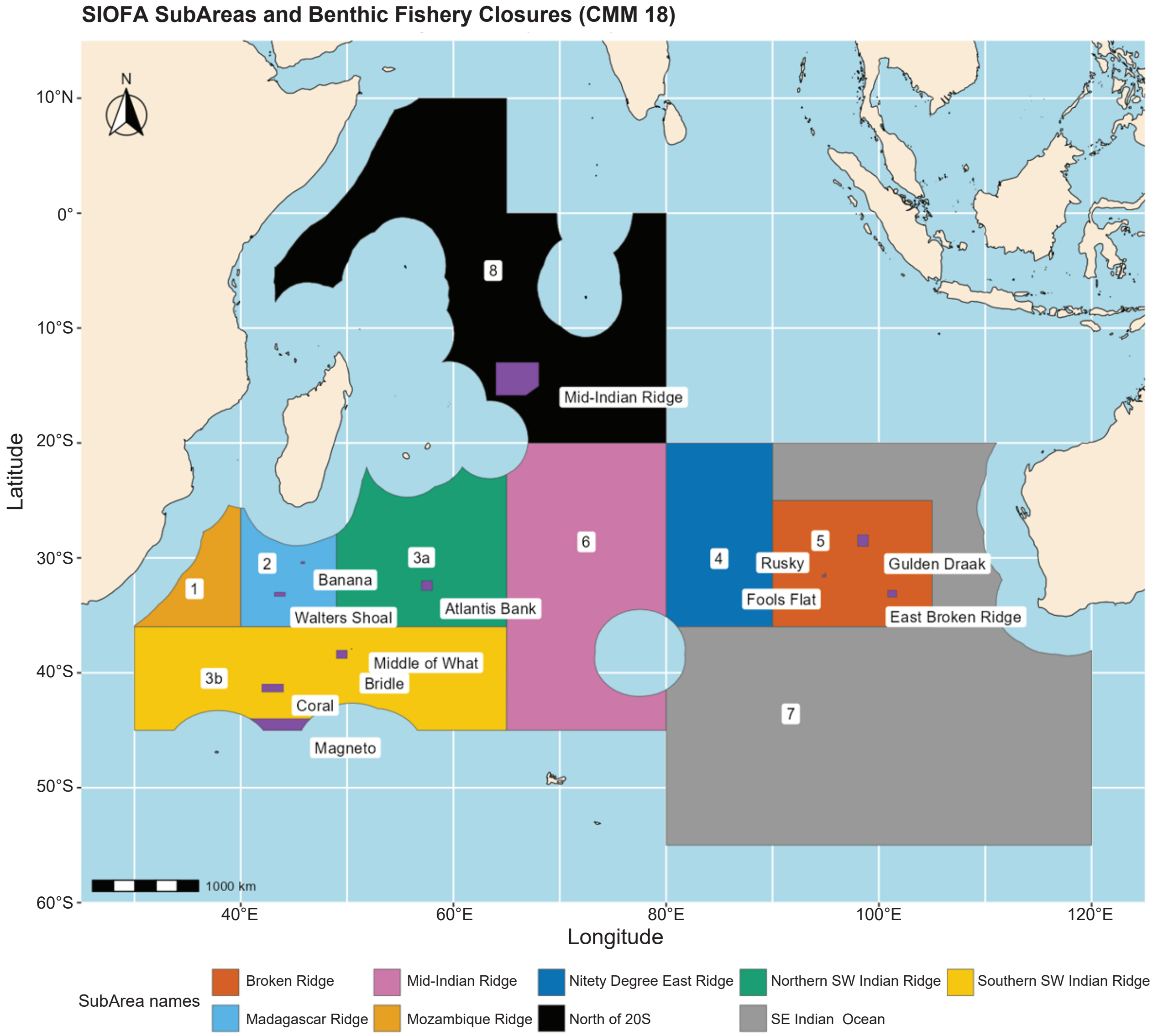


Fig. 1. The SIOFA Area and Subareas (source: SIOFA Spatial database). The map highlights SIOFA Benthic Fishery Closures (in purple) as defined in CMM 18(2025) (Table 1 and 2). All the benthic fishery closures have been labelled by name for easier recognition. Reproduced from the SIOFA Ecosystem Summary 2026 (SIOFA Secretariat 2006).

development. Its founding agreement legally embeds an ecosystem approach as part of its mandate, creating a compelling imperative to translate this principle into action (SIOFA 2006, Article 4a) and placing EAFM at the heart of SIOFA's legal identity and operational mission. However, as with many RFMOs (*e.g.*, Juan-Jordá *et al.,* 2018; Haas *et al.,* 2020; Shen and Song, 2023), translating this principled commitment into consistent and effective practice has been a significant challenge.

This perspective paper documents SIOFA's journey in meeting that challenge, arguing that its pragmatic, tiered approach provides a context-specific example of how data-limited RFMOs can operationalize EAFM through adaptive learning—building on, rather than replicating, experiences from other bodies.

Early Practices: Pragmatic Management in a Data-Limited Context

Faced with the imperative to implement EAFM amidst the data-scarce reality common to many recently established RFMOs (*i.e.*, after the early 2000s), SIOFA's initial path was necessarily pragmatic. Before the development of a comprehensive, internal evidence base, the organization employed adaptive strategies to fulfil its conservation mandate. These early initiatives can be broadly categorized into two complementary approaches:

precautionary alignment with other *management* bodies and proactive, evidence-based conservation driven by targeted research, each demonstrating a flexible response to varying levels of information availability.

Precautionary and Harmonized Management: Interim Measures for Seabirds and VMEs

In areas where SIOFA-specific data were initially lacking, such as for seabird bycatch and the location of Vulnerable Marine Ecosystems (VMEs), the organization adopted a precautionary strategy in line with the Agreement. Recognizing the high potential for serious and irreversible harm, SIOFA looked to measures already established by other, more data-rich RFMOs operating in other regions. By harmonizing its Conservation and Management Measures (CMMs; SIOFA 2025)—for example, adopting standardized bycatch mitigation protocols for seabirds and established thresholds for identifying and protecting VMEs—SIOFA achieved several critical objectives. First, it enacted a precautionary safeguard without delay, erring on the side of conservation while local data were being accumulated. This is best exemplified with the adoption of the Northwest Atlantic Fisheries Organization (NAFO, 2026) threshold for Vulnerable Marine Ecosystems (VME) encounters with bottom trawl gear (Article 22.1 of the NAFO Conservation and Enforcement Measures) while SIOFA was building up its own knowledge of VME indicator taxa bycatch in its own area; a practical solution, even if perhaps not scientifically sound as it assumed the SIOFA Area would have similar densities and distributions of benthic taxa as the northwest Atlantic. Second, this approach promoted management consistency for fishing vessels operating across RFMO boundaries, thereby simplifying compliance and enhancing overall governance effectiveness (Cullis-Suzuki and Pauly, 2010; Pentz *et al.,* 2018). A good example of this is the adoption of the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR, 2013) threshold for VME encounters with demersal longline gear (CM 22-07), which allows vessels targeting Patagonian toothfish (*Dissostichus eleginoides*) in the southern areas of SIOFA to implement a single measure across boundaries. This strategy demonstrated a practical understanding that in a data-limited context, leveraging existing knowledge is a responsible and efficient interim step in EAFM (Fletcher *et al.,* 2014; FAO, 2025).

The decision to harmonize measures for seabirds and VMEs with other RFMOs was not merely administrative; it represented a strategic choice grounded in the precautionary approach. This approach acknowledged the high ecological stakes and the improbability of obtaining perfect, SIOFA-specific data in the short term. However, this strategy also carried inherent limitations. Dependence on external benchmarks raised questions about the universal applicability of measures developed for different ecological and socio-economic contexts. Despite this potential drawback, the approach was justified as a necessary, risk-averse strategy to prevent irreversible damage while building local knowledge, in line with the SIOFA Agreement (SIOFA 2006, Article 4c).

Proactive Management: Evidence-Based Conservation for Deepwater Sharks

Conversely, where specific risks were identified and the capacity for targeted assessment existed, SIOFA demonstrated its ability to conduct proactive, science-driven management. A clear example is SIOFA's approach to deepwater sharks; commissioning a dedicated ecological risk assessment (Hobday *et al.,* 2011) provided the necessary evidence to identify some species as a high priority for conservation. This targeted research used the Sustainability Assessment for Fishing Effects (SAFE) methodology to evaluate 94 chondrichthyan species across three gear types (demersal trawl, midwater trawl, demersal longline), using three distribution mapping sources (AquaMaps, FAO GeoNetwork, IUCN Red List). The analysis identified 14 deepwater shark species at high or extreme vulnerability to demersal longline fishing, directly informing the development of CMM 12 (SIOFA, 2025), which established a ban on targeting these species and other measures to mitigate risks to shark populations from bycatch. This case illustrates SIOFA's commitment to moving beyond general precaution to targeted, evidence-based action when specific information becomes available, showcasing a capacity for nuanced management tailored to distinct ecological challenges.

The ecological risk assessment for deepwater sharks exemplified a more targeted, data-generating approach. The methodology itself—assessing a species' susceptibility to the fishery and its potential for recovery—provided a structured framework for prioritizing conservation actions. This moved SIOFA from a position of general precaution to one of specific, evidence-based priority-setting. The subsequent evolution of CMM 12, which recently also included some spatially explicit measures (a catch limit for one species in SIOFA Subarea 2, a 5-nautical-mile move-on rule in SIOFA Subarea 4 when shark catch exceeds 50% of haul, and a ban on bottom longline fishing in Subarea 5 until a stock assessment is completed and endorsed), demonstrated an ability to translate complex scientific assessments into actionable management. This case highlights a critical success factor: the availability of scientific expertise and resources to conduct such targeted assessments, which may not be feasible for all ecosystem components simultaneously.

Synthesis: Establishing a Baseline of Adaptive Management

Together, these two approaches established a baseline of adaptive management for SIOFA, proving the organization's ability to act decisively across a spectrum of information availability. However, these strategies also revealed their inherent limitations. The precautionary approach, while vital, remained inherently reactive and dependent on external benchmarks (*e.g.*, VME thresholds set for other geographic areas and taxa). Similarly, the targeted assessments, though effective, were resource-intensive and focused on single issues (*e.g.*, risk from deepwater shark bycatch). Consequently, a more integrated, sustainable, and self-sufficient solution was needed to fully empower the Scientific Committee and systematically implement EAFM across all facets of SIOFA's remit. This recognition set the stage for the development of a more comprehensive tool.

The Implementation Challenge: The Need for an Integrated Evidence Base

The limitations of the early practices culminated in the recognition of a systemic bottleneck. While valuable, both the precautionary and targeted-risk approaches were inherently fragmented. They addressed symptoms of data scarcity rather than the underlying cause: the absence of a centralized, accessible, and ongoing evidence synthesis process. The core of this challenge was a practical one: the SIOFA Scientific Committee, the subsidiary body tasked with providing ecosystem advice to the Meeting of the Parties, faced significant difficulties in efficiently accessing and synthesizing the fisheries data collected by the Secretariat. These data, while existent, were not readily available in a format tailored for scientific analysis aimed at answering ecosystem-scale questions and were not accessible to all the members of the Scientific Committee. The need was not just for more data, but for a dedicated mechanism to transform disparate data into coherent ecosystem intelligence (Levin *et al.,* 2009) that could be accessed by the SIOFA Scientific Committee.

This gap meant that the Scientific Committee's ability to provide integrated ecosystem advice was constrained. For instance, understanding the cumulative impact of fisheries on different trophic levels or identifying synergistic effects between various pressures remained a significant challenge. This potentially limited the Committee's ability to move beyond reactive advice on specific issues towards proactive, strategic guidance on fisheries management accounting for ecosystem considerations. Moreover, this accessibility barrier risked constraining EAFM to a series of discrete projects rather than an embedded, guiding principle. Without a mechanism to easily synthesize data on species distributions, bycatch events, and environmental interactions, identifying emerging trends in fisheries impacts on the ecosystem remained a formidable task. It became clear that to truly transition from principle to practice, SIOFA needed to bridge this gap between data collection and scientific analysis, thereby fostering a more direct and efficient science-policy interface.

A Solution: The Development of the SIOFA Ecosystem Summary

In direct response to the need for an integrated evidence base, SIOFA initiated the development of an internal synthesis tool: the SIOFA Ecosystem Summary (SIOFA Secretariat, 2026), developed in 2022 and published for the first time in 2023. Similar in function to tools already developed in other RFMOs, *e.g.* the NAFO Ecosystem Summary Sheets or the International Council for the Exploration of the Sea (ICES) ecosystem overviews (Roux and Pedreschi, 2024), and comparable ecosystem synthesis products being developed or used by ICCAT, IOTC, and IATTC — the SIOFA Ecosystem Summary was conceived as a practical bridge between data management and scientific analysis, the Summary is a living document curated by the SIOFA Secretariat in close consultation with the Scientific Committee and updated annually ahead of the Scientific Committee's main meeting. Its specific aim is to synthesize available fisheries and ecological data into an accessible format for the Scientific Committee (Fig. 2), thus streamlining the Committee's access to information, thereby empowering efficient and holistic ecosystem assessments.

The development of the SIOFA Ecosystem Summary can be understood as an exercise in creating an institutional knowledge system. The process involved not just technical data compilation but also important sociological elements, such as building trust and a common language between the data-holding Secretariat and the science-providing Committee, as well as across SIOFA parties. The iterative, collaborative nature of its development was crucial for ensuring the tool's practical utility. For example, initial versions focused on basic fishery metrics, but through feedback, evolved to include indicators of ecosystem health, such as bycatch ratios of non-target species or spatial overlaps with known VME indicators and fisheries area closures. This evolution underscores the tool's role as what theory refers to as a 'boundary object' (Star and Griesemer, 1989; Cooke *et al*., 2023), an artifact that is both adaptable to different viewpoints and robust enough to maintain a common identity across social worlds (*e.g.*, scientists, managers), thereby facilitating communication across different institutional roles. This framing offers a key conceptual takeaway for other RFMOs: that investing in shared information artifacts can serve as a pragmatic mechanism for building trust, aligning expectations, and fostering collaboration between data holders, scientists, and decision-makers. In contexts where formal top-down EAFM frameworks may be impractical, such boundary objects can provide a tangible entry point for operationalizing ecosystem-informed management, even with limited resources.

The Secretariat, rather than a dedicated Work Group like in other RFMOs (*e.g.*, NAFO), took the lead in

SIOFA | APSOI
Southern Indian Ocean Fisheries Agreement
Accord relatif aux Pêches dans le Sud de l'Océan Indien

SIOFA Ecosystem Summary 2026

Contents

Fig. 2. The SIOFA Ecosystem Summary 2026 heading and table of contents (source: source: SIOFA Secretariat 2026).

collating data from fishing activities, observer reports, and scientific surveys, focusing on synthesizing information relevant to EAFM, such as species catch distributions (including non-target species), bycatch events, and interactions with vulnerable ecosystem indicators. This synthesis transformed raw data into a structured overview, highlighting trends, patterns, and knowledge gaps. For instance, a key finding is the elaboration of previously unclear ecological trends and the reporting of key outcomes of SIOFA research projects (*e.g.* on benthic species distribution maps within the SIOFA Area), providing a significantly clearer picture of the ecosystem context in which fisheries operate, as well as a record of the evolution of ecosystem knowledge within SIOFA.

The Ecosystem Summary is not a static report but an evolving tool. Its structure and content are continuously refined based on feedback from the Scientific Committee, ensuring it remains tailored to their advisory needs. By providing a consolidated baseline of information, the Summary directly facilitates the Committee's work, allowing them to focus on interpretation and risk analysis rather than data gathering. This tool, therefore, represents a significant step towards institutionalizing EAFM within SIOFA, creating a sustainable mechanism to support science-based advice and moving the organization from ad-hoc solutions towards a systematic, data-informed approach to fisheries management.

So far, the SIOFA Ecosystem Summary, contributed to help the Scientific Committee and the other SIOFA bodies to comprehensively visualize, for the first time, the current status of knowledge on ecosystem effects. This has improved the capacity of the Scientific Committee to direct the Secretariat on data practices (*e.g.*, linkages between the catch effort and scientific observation data), assess the observer coverage in fisheries, the bottom fishing footprint and the extent of bycatch, particularly for species of sharks covered under SIOFA CMM 12 (SIOFA, 2025). While the Summary does not itself enact management measures, it provides the evidence base that enables the Scientific Committee to formulate advice and prioritize issues—such as the refinement of spatially explicit measures in CMM 12 — thereby facilitating the translation of ecosystem intelligence into actionable conservation outcomes.

Looking Ahead: Consolidating the Practice and Future Directions

SIOFA's journey in implementing EAFM demonstrates a pragmatic evolution—from necessary interim measures to the development of a dedicated tool for integrated governance (Fig. 3 – A schematic representation of the SIOFA EAFM pathway through its history, and the role of the Ecosystem Summary within it.).

The initial strategies of precautionary alignment and targeted risk assessments proved the organization's capacity for adaptive management. The subsequent development of the SIOFA Ecosystem Summary represents a strategic advancement, addressing the core challenge of data accessibility and creating a sustainable foundation for ecosystem-based advice to manage fisheries. This progression underscores that effective EAFM implementation is not a binary state but a continuous process of adaptation and institutional learning.

The primary lesson that SIOFA learnt from its experience is the strategic value of a flexible, phased, and adaptive approach. Rather than being paralyzed by the ideal of a comprehensive EAFM system from the outset, SIOFA adopted a learning-by-doing philosophy. While other frameworks are also valuable, SIOFA's experience demonstrates the efficacy of a bottom-up, internally driven process that builds institutional capacity and ownership from the start. This tiered strategy—starting with harmonization, advancing to targeted assessments, and culminating in a dedicated knowledge tool—is a good example of EAFM implementation in newer or data-limited bodies. It demonstrates that EAFM is an iterative cycle of action, evaluation, and adaptation, effectively balancing urgent conservation needs with the long-term goal of evidence-based, ecosystem-level management of fisheries.

However, SIOFA can learn many lessons from EAFM implementation experience in other organizations which have progressed further along the way. For example, NAFO has developed a comprehensive roadmap to EAFM with a tiered approach (Koen-Alonso *et al.,* 2019) and is possibly one of the RFMOs which have progressed the most (Fletcher, 2020). Similarly to NAFO, the International Council for the Exploration of the Sea (ICES) has developed comprehensive system of ecosystem overviews, fishery summaries and risk assessments, which are weaved into a Framework for Ecosystem-Informed Science and Advice (Roux and Pedreschi, 2024), and have become the main tools for their EAFM advice. Other RFMOs, including ICCAT, IOTC, and IATTC, are also developing ecosystem synthesis products—such as pilot EcoCards and Ecosystem Fisheries Overviews—that serve a broadly similar function in synthesizing information to support scientific advice, even if the specific formats vary. A common feature of the more established approaches, exemplified by NAFO and ICES, is the use of dedicated Working Groups as a mechanism to advance cumulative impact analysis—a mechanism that SIOFA could consider replicating as capacity allows..

While several RFMOs and institutions—including NAFO, ICES, and the Western and Central Pacific Fisheries Commission (WCPFC)—are advancing ecosystem monitoring through quantitative indicators and spatial modelling (Fletcher, 2020), SIOFA's path forward must reflect its data-limited context and institutional capacity. Looking ahead, SIOFA's work could focus on enhancing

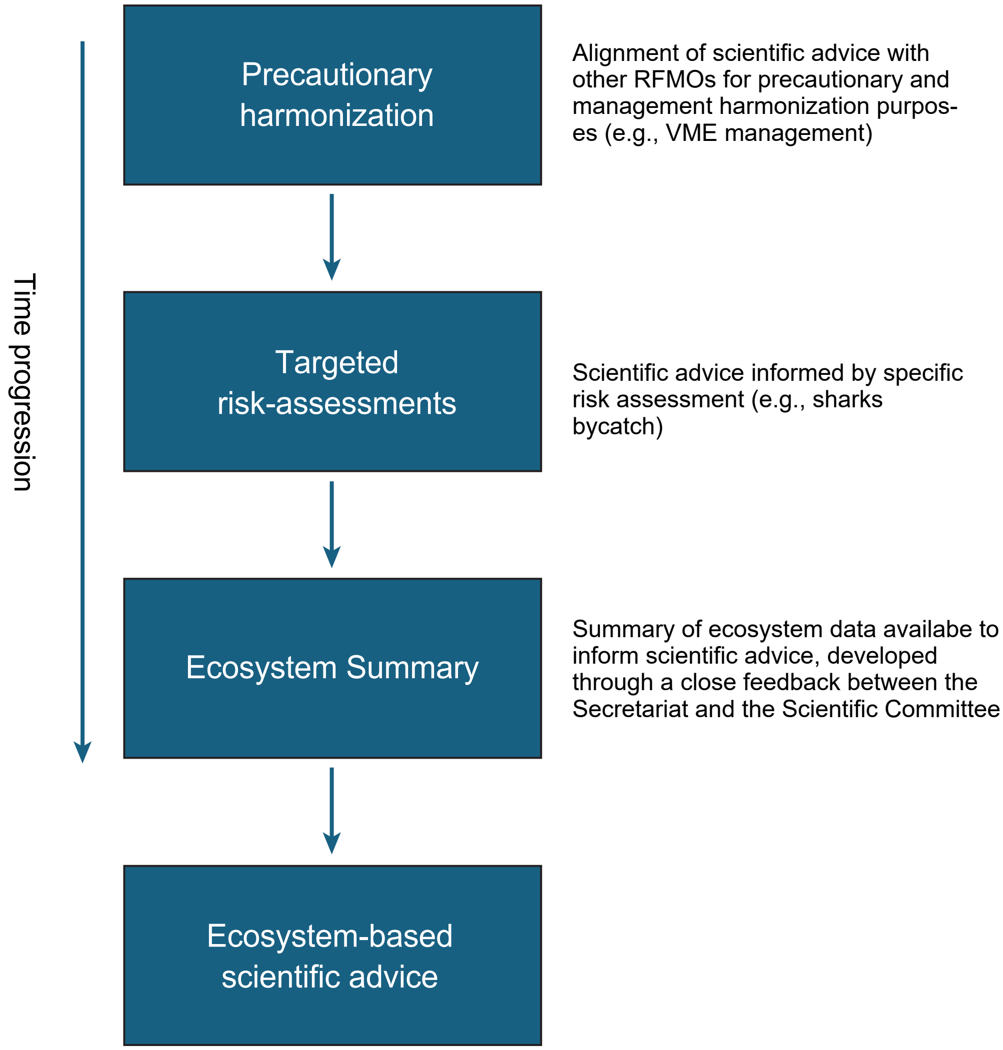


Fig. 3. A schematic representation of the SIOFA EAFM pathway through its history, and the role of the Ecosystem Summary within it.

the analytical sophistication of the Ecosystem Summary and its utility for evaluating cumulative impacts. This could involve developing quantitative ecosystem indicators to track trends over time or employing spatial modelling to predict interactions under different management scenarios. However, the Summary should not replace—but rather guide—dedicated scientific research, such as planned research cruises or specific projects, to fill persistent knowledge gaps, particularly concerning benthic ecosystems and the impacts of climate change. Indeed, integrating climate change effects (Pinsky and Mantua, 2014)— which alter ecological baselines and create novel species interactions—will be a significant scientific challenge, testing the adaptability of any management framework.

Furthermore, a critical frontier for SIOFA will be to more fully integrate the human dimension of EAFM. While this paper has focused on ecological and governance challenges, achieving true sustainability requires addressing socio-economic considerations and equity (FAO, 1995; Jentoft and Chuenpagdee, 2009). Socio-economic dimensions remain underdeveloped across the RFMO landscape (Fletcher, 2020), presenting a shared frontier for future integration. Future efforts could explore how the Ecosystem Summary, or a complementary tool, might incorporate data on social and economic outcomes, and how stakeholder engagement processes—particularly with fishing communities and industry—can be strengthened to ensure management measures are not only ecologically sound but also socially equitable and economically viable.

The intermediate goal could be to use the Summary not only to inform fisheries management advice but also to identify knowledge gaps and priority areas, thereby stimulating targeted strategies to strengthen the evidence base. However, the ultimate goal for SIOFA could be to create a virtuous cycle that fosters a culture of adaptive management, in which the Ecosystem Summary is not just a reporting tool but a central component of a dynamic feedback loop—continuously informing and refining research priorities and management decisions in response to a changing ecosystem.

Yet this vision must be pursued with clear-eyed realism. Despite promising progress, SIOFA's path toward fully realized EAFM faces three interrelated challenges. First, there is an inherent risk that the Ecosystem Summary could evolve into a procedural formality rather than a catalyst for actionable advice; its long-term value depends on remaining dynamic and directly relevant to pressing management questions. Second, even the most robust scientific tools cannot automatically overcome political hurdles: the translation of the Scientific Committee's advice—however well-informed by the Summary—into effective Conservation and Management Measures remains a consensus-driven political process (Mooney-Seus and Rosenberg, 2007) among Contracting Parties with potentially competing economic interests and possibly limited resources to consider the Scientific Committee advice and translate it into policy. Third, the sustainability of this approach hinges on securing ongoing institutional commitment and resources to maintain and update the Summary, ensuring it does not become a static snapshot but continues to serve as a living core of SIOFA's adaptive management cycle.

Acknowledging these considerations is not a critique of the progress made, but a recognition that the journey from principle to practice is an ongoing negotiation between scientific innovation, institutional will, and political reality. In conclusion, SIOFA's experience offers a replicable model for moving from the principle of EAFM to its tangible practice. By embracing adaptive management, bridging data gaps with pragmatic tools, and maintaining a clear focus on long-term sustainability, SIOFA is charting a viable course for achieving its mandate. This journey—echoing Gandhi's observation that "Earth provides enough to satisfy every man's needs, but not every man's greed"—reflects a commitment to a balanced, equitable, and ecosystem-conscious future for fisheries governance in the Southern Indian Ocean.

References

Cooke, S. J., Cook, C. N., Nguyen, V. M., Walsh, J. C., Young, N., Cvitanovic, C., Grainger, M. J., Randall, N. P., Muir, M., Kadykalo, A. N., Monk, K. A., and Pullin, A. S. 2023. Environmental evidence in action: on the science and practice of evidence synthesis and evidence-based decision-making. *Environmental Evidence*, **12(1)**, 10p. https://doi.org/10.1186/s13750-023-00302-5

CCAMLR. 2013. Conservation Measure 22-07. Interim measure for bottom fishing activities subject to Conservation Measure 22-06 encountering potential vulnerable marine ecosystems in the Convention Area, 3 p.

Cullis-Suzuki, S., and Pauly, D. 2010. Failing the high seas: A global evaluation of regional fisheries management organizations. *Marine Policy*, **34(5)**, 1036–1042. https://doi.org/10.1016/j.marpol.2010.03.002

FAO. 1995. Code of Conduct for Responsible Fisheries. Food and Agriculture Organization of the United Nations. Rome, Italy. 41p.

FAO. 2003. The Ecosystem Approach to Fisheries. FAO Technical Guidelines for Responsible Fisheries No. 4, Suppl. 2. Food and Agriculture Organization of the United Nations. Rome, Italy.

FAO. 2025. Toolbox for the Ecosystem Approach to Fisheries (EAF). https://www.fao.org/fishery/en/eaf-net/toolbox/about . Last accessed September 2025

Fletcher, W. J. 2008. Implementing an ecosystem approach to fisheries management: lessons learned from applying a practical EAFM framework in Australia and the Pacific. In *The ecosystem approach to fisheries,* 112–124). Wallingford UK: CABI. https://doi.org/10.1079/9781845934149.0112

Fletcher, W. J., Shaw, J., Metcalf, S. J., and Gaughan, D. J. 2010. An ecosystem based fisheries management framework: the efficient, regional-level planning tool for management agencies. *Marine Policy*, **34(6)**, 1226–1238. https://doi.org/10.1016/j.marpol.2010.04.007

Fletcher, W. J., and Bianchi, G. 2014. The FAO–EAF toolbox: Making the ecosystem approach accessible to all fisheries. *Ocean & Coastal Management*, **90**, 20–26. https://doi.org/10.1016/j.ocecoaman.2013.12.014

Fletcher, W. J. 2020. A review of the application of the FAO ecosystem approach to fisheries (EAF) management within the areas beyond national jurisdiction (ABNJ). Rome, FAO. https://doi.org/10.4060/cb1509en

Haas, B., J. McGee, A. Fleming, and M. Haward. 2020. Factors influencing the performance of regional fisheries management organizations. *Marine Policy,* **113**:103787. https://doi.org/10.1016/j.marpol.2019.103787

Hobday, A. J., Smith, A. D. M., Stobutzki, I. C., Bulman, C., Daley, R., Dambacher, J. M., Deng, R. A, Dowdney, J., Fuller, M., Furlani, D., Griffiths, S. P., Johnson, D., Kenyan, R., Knuckey, I. A., Ling, S. D., Pitcher, R., Sainsbury, K. J., Sporcic, M., Smith, T., Turnbull, C., and Zhou, S. 2011. Ecological risk assessment for the effects of fishing. *Fisheries Research*, **108(2–3)**, 372–384. https://doi.org/10.1016/j.fishres.2011.01.013

Holling, C. S. 1978. Adaptive environmental assessment and management. John Wiley & Sons.

Jentoft, S., and Chuenpagdee, R. 2009. Fisheries and coastal governance as a wicked problem. *Marine policy*, **33**(4), 553–560. https://doi.org/10.1016/j.marpol.2008.12.002

Juan-Jordá, M. J., Murua, H. Arrizabalaga, H., Dulvy, N., and Restrepo, V. 2018. Report card on ecosystem-based fisheries management in tuna regional fisheries management organizations. *Fish and Fisheries* **19(2)**: 321–339. https://doi.org/10.1111/faf.12256

Koen-Alonso, M., Pepin, P., Fogarty, M. J., Kenny, A., and Kenchington, E. 2019. The Northwest Atlantic Fisheries Organization Roadmap for the development and implementation of an Ecosystem Approach to Fisheries: structure, state of development, and challenges. *Marine Policy*, **100**, 342–352. https://doi.org/10.1016/j.marpol.2018.11.025

Levin, P. S., Fogarty, M. J., Murawski, S. A., and Fluharty, D. 2009. Integrated ecosystem assessments: developing the scientific basis for ecosystem-based management of the ocean. *PLoS biology*, **7(1)**, e1000014. https://doi.org/10.1371/journal.pbio.1000014

Mooney-Seus, M. L., and Rosenberg, A. A. 2007. Best Practices for High Seas Fisheries Management: Lessons Learned. Chatham House.

NAFO. 2026. NAFO Conservation and Enforcement Measures. Serial No. N7705 NAFO/COM Doc. 26-01 (Revised), 213 p.

Pentz, B., Klenk, N., Ogle, S., and Fisher, J. A. 2018. Can regional fisheries management organizations (RFMOs) manage resources effectively during climate change?. *Marine Policy*, **92**, 13–20. https://doi.org/10.1016/j.marpol.2018.01.011

Pinsky, M. L., and Mantua, N. J. 2014. Emerging adaptation approaches for climate-ready fisheries management. *Oceanography*, **27**(4), 146–159. https://doi.org/10.5670/oceanog.2014.93

Plagányi, É. E., Punt, A. E., Hillary, R., Morello, E. B., Thébaud, O., Hutton, T., Pillans, R. D., Thorson, J. T., Fulton, E. A., Smith, A. D. M., Smith, F., Bayliss, P. Haywood, M., Lyne, V., and Rothlisberg, P. C. 2014. Multispecies fisheries management and conservation: tactical applications using models of intermediate complexity. *Fish and Fisheries*, **15**(1), 1–22. https://doi.org/10.1111/j.1467-2979.2012.00488.x

Ramirez-Monsalve, P., Raakjær, J., Nielsen, K. N., Laksá, U., Danielsen, R., Degnbol, D., Ballesteros, M., and Degnbol, P. 2016. Institutional challenges for policy-making and fisheries advice to move to a full EAFM approach within the current governance structures for marine policies. *Marine Policy*, **69**, 1–12. https://doi.org/10.1016/j.marpol.2016.03.016

Roux, M. J., and Pedreschi, D. 2024. ICES framework for ecosystem-informed science and advice (FEISA).

Shen, H., and Song, L. 2023. Implementing ecosystem approach to fisheries management in the western and central pacific fisheries commission: challenges and prospects. *Fishes*, **8(4)**, 198. https://doi.org/10.3390/fishes8040198

SIOFA. 2006. The final Act of the Conference on the Southern Indian Ocean Fisheries Agreement. https://siofa.org/sites/default/files/documents/SIOFA-Agreement-Digital-ENG.pdf

SIOFA. 2025. Conservation and Management Measures (CMMs). https://siofa.org/management/CMM. Last accessed September 2025

SIOFA Secretariat. 2026. SIOFA Ecosystem Summary 2026. Southern Indian Ocean Fisheries Agreement (SIOFA), 72 p. https://siofa.org/sites/default/files/files/SIOFA-Ecosystem-Summary-2026.pdf

Star, S. L., and Griesemer, J. R. 1989. Institutional ecology translations and boundary objects: Amateurs and professionals in Berkeley's Museum of Vertebrate Zoology, 1907–39. *Social studies of science*, **19(3)**, 387–420. https://doi.org/10.1177/030631289019003001

Walters, C. J. 1986. Adaptive management of renewable resources. Macmillan Publishers Ltd.

J. Northw. Atl. Fish. Sci., Vol. 57, Special Issue: 79–91 Publication (Upload) date: 11 Sep. 2026
Conference article

Advancing an Ecosystem Approach to Fisheries Management in the Northeast Atlantic: ICES's Scientific Framework, Advice Products, and Implementation Pathways

Lara Salvany *, **Neil Campbell, Inigo Martinez, Anne Cooper and Colm Lordan**
*corresponding author for this work

International Council for the Exploration of the Sea. 44-46 HC Andersens Boulevard, Copenhagen, Denmark

Salvany, L., Campbell, N., Martinez, I., Cooper, A., and Lordan, C. 2026. From Principle to Practice: a pragmatic pathway for Ecosystem-Based Fisheries Management in a data-limited RFMO. *J. Northw. Atl. Fish. Sci.*, **57(1)**: 79–91. https://doi.org/10.2960/J.v57.m761

Abstract

Achieving marine management objectives and long-term sustainability requires moving beyond conventional, single-species management, towards an Ecosystem Approach to Fisheries Management (EAFM), that accounts for complex ecological interactions, cumulative human pressures, and environmental variability. The International Council for the Exploration of the Sea (ICES) advances EAFM in the Northeast Atlantic by providing scientific frameworks and advice products that address fundamental aspects of EAFM: understanding the ecosystem's influence on fisheries, quantifying fisheries' impact on the wider ecosystem, contextualizing fisheries among other pressures, and analyzing trade-offs between competing management objectives. Examples are provided for ICES integration of ecosystem information into advice, including the ecosystem-based fishing mortality reference point (F_{ECO}), the regional benthic impact assessments and trade-off analysis and the ICES Framework for Ecosystem-Informed Science and Advice (FEISA). These examples illustrate how ICES is moving from the single species model and contextual ecosystem assessment towards more operational ecosystem-informed advice. Despite progress, key challenges remain, including a fragmented governance structure and a lack of clear, formalized process translating ecosystem advice into management actions. Furthermore, there are significant data gaps concerning social and economic dimensions that need to be addressed to truly achieve a comprehensive EAFM.

Keywords: Ecosystem Approach to Fisheries Management (EAFM); Ecosystem-Based Management (EBM); Ecosystem-Informed Advice; Fisheries Management; Northeast Atlantic.

Introduction

Achieving long-term sustainability goals for marine fisheries requires management approaches that account for ecological interactions, cumulative human pressures, environmental variability, and social and economic dimensions. This has driven a shift from traditional single-stock and sector-based fisheries management towards the Ecosystem Approach to Fisheries Management (EAFM), which applies ecosystem-based management principles specifically to fisheries. In the Northeast Atlantic, ICES has played a central role in advancing this transition by developing scientific frameworks and advice products that incorporate ecosystem information into fisheries advice and support more integrated decision-making.

EAFM requires a systems-thinking approach to fisheries as interconnected socio-ecological systems. Its overarching goal is to use fisheries resources sustainably, conserve biodiversity, and support robust decision-making in a changing climate, while ensuring public participation and adhering to global governance principles. The implementation of EAFM can be separated into three main components representing the key dimensions of a fishery system: ability to achieve, ecological well-being, and human well-being (FAO, 2021). Ability to achieve includes elements such as governance and policy frameworks, environmental and external drivers, and stakeholder engagement. Ecological well-being includes target species management, protection of vulnerable species, and bycatch monitoring, while human well-being covers economic performance, social and cultural benefits, and equity.

Globally, the Northeast Atlantic is considered a leading region in the implementation of Ecosystem Based Management (EBM). The International Council for the Exploration of the Sea (ICES) contributes to this progress by providing a robust scientific framework and a suite of products targeting four fundamental aspects: understanding the influence of the marine ecosystem on fisheries; quantifying the impact of fisheries on the wider ecosystem; placing fisheries within the context of other marine activities and pressures; and analyzing the trade-offs between competing management objectives. ICES provides advisory services to regional and international fisheries management organizations, Regional Seas Conventions, and governments. It is a recognized and trusted independent scientific advisor, with advice grounded in best available peer-reviewed science, developed through transparent and participatory processes, and agreed by consensus (ICES, 2023b).

This paper synthesizes how ICES operationalizes EAFM in the Northeast Atlantic through complementary science and advice products. We examine the Ecosystem Overviews, advice on ecosystem effects on fisheries, assessments of fisheries impacts on ecosystems, guidance on EAFM implementation pathways, and the ICES Framework for Ecosystem-Informed Science and Advice (FEISA; Roux and Pedreschi, 2024). We then discuss how these products collectively support ecosystem-informed advice, where limitations remain, and what is needed to strengthen their operational use in fisheries management.

ICES implements EAFM across multiple levels of its advisory system, from data collection and stock assessment methods to integrated ecosystem analysis and advice. This includes expanding monitoring programmes to incorporate ecosystem information, environmental drivers, and multispecies interactions alongside traditional fisheries data, reflecting the broader data requirements of an ecosystem approach (FAO, 2003; FAO, 2021; ICES, 2024a).

Within ICES stock assessments and advisory framework, ecosystem information is incorporated through ecosystem-informed assessment methods where available, mixed-fisheries analyses, consideration of environmental variability, and evaluation of trade-offs among species, fisheries, and ecosystem components. In this way, ICES complements its established fisheries advice with ecosystem information that supports decision-making consistent with EAFM objectives.

To make EAFM applicable across the diversity of commercial fisheries managed in the Northeast Atlantic, the ICES advisory framework applies the Maximum Sustainable Yield (MSY) or a Precautionary Approach (PA) to all 260 ICES stocks, spanning data-rich stocks with analytical assessments and more data-limited stocks (ICES, 2023c). While MSY and PA reference points are primarily derived from single-species population dynamics, ecosystem considerations are incorporated through adjustments to reference points, the use of ecosystem-informed assessment methods where available, and through the broader advisory process, including mixed-fisheries analysis, consideration of environmental variability, and the evaluation of trade-offs between species and ecosystem components. As a result, MSY- and PA-based advice is complemented by ecosystem information to better support decision-making that is consistent with the objectives of EAFM (ICES, 2023b; ICES, 2023c; ICES, 2025a).

Results

ICES supports EAFM through a set of complementary science and advice products that operate at different levels of the advisory system. Ecosystem Overviews provide regional ecological and governance context; ecosystem-informed fisheries advice incorporates environmental variability and multispecies interactions into stock advice; spatial assessments quantify fisheries impacts on habitats, vulnerable ecosystems, and non-target species; implementation guidance supports uptake by management organizations; and FEISA provides an integrating framework for linking indicators, risk assessment, and advice. The following sections describe these products and illustrate how, collectively, they contribute to more operational ecosystem-informed advice.

Ecosystem overviews: regional context for EAFM

The ICES Ecosystem Overviews (EOs) are a key scientific product developed to support an Ecosystem-Based Management (EBM) of marine environments. The EOs illustrate how ICES has expanded its scope beyond fisheries to consider a broader range of human activities and the pressures they exert on marine ecosystems (ICES, 2023a). They also highlight the complexity of governance in these regions, where multiple competent authorities, including national governments, the European Union, Regional Fisheries Management Organizations (RFMOs), and Regional Seas Conventions, implement policies and legislation across sectors that may not always be fully aligned.

The Ecosystem Overviews apply a risk-based assessment approach, to identify and prioritize the top pressures and associated activities on which management actions should focus on these complex governance seascapes. ICES has published EOs for eleven ecoregions in the Northeast Atlantic, from the Gulf of Cadiz to the Central Arctic Ocean, including the Baltic Sea, and these are updated in cycles of approximately five years.

The EOs identify the main pressures affecting ecosystem components through the main human activities in each ecoregion (Fig. 1). This identification is done by the specialized regional Ecosystem Approach methods groups which include expertise across the different ecosystem components (see Fig. 1, right column) and is complemented by other expert groups where a knowledge gap is identified. The risk-based assessment uses a driver–pressure–state linkage framework which scores all direct pressures and human activities in an ecoregion by examining the temporal and spatial scale and degree of impact of each activity-pressure pair on the ecosystem components. The assessment is semi-quantitative,

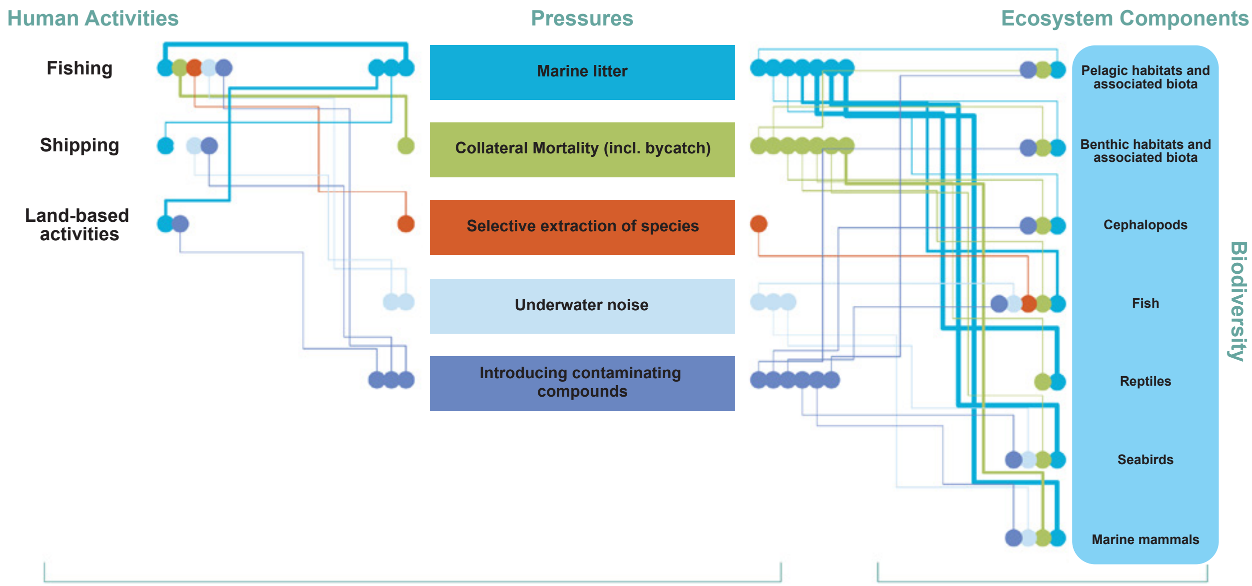


Fig 1. Example of an assessment summary from the Oceanic Northeast ecoregion (ICES, 2025b) including most relevant regional pressures, human activities, and state of ecosystem components (representing biodiversity). The width of the lines indicates the relative importance of the main individual links. Human activities and pressures are listed in decreasing order of relative contribution to the total risk score. The absence of a line does not necessarily imply a total absence of any link; only the main contributors are shown in the figure.

informed by both quantitative information where available and qualitative information (*e.g.* expert judgement) where little or no quantitative information is available. The risk assessment is produced following the guidelines developed in the ICES Workshop on methods and guidelines to link human activities, pressures and state of the ecosystem in Ecosystem Overviews (WKTRANSPARENT; ICES, 2021) and detailed in the ICES Ecosystem Overviews Technical Guidelines (ICES, 2023a).

The Ecosystem Overviews highlight the most important pressures, in order of importance, with the main links to the sectors and to the state of the ecosystem components (see Fig. 1). These should be pressures that can be managed at the regional level. The assessments also produce outcomes at a finer resolution, with the complete list of activities and pressures available in the working groups' scientific reports and/or published in the literature (Pedreschi *et al.* 2023). These main outcomes are represented in a wire diagram, an example of which is shown in Fig. 1.

The EOs provide contextual regional advice and support cross-sector integration, helping to situate otherwise isolated sectorial advice (*i.e.* advice on offshore renewables, VMEs, bycatch, etc.) within a broader ecosystem context. They also identify the most pressing ecosystem risks, which can be used by the scientific community to develop more holistic ecosystem models and environmental indicators, and by decision-makers to concentrate policy efforts on the most pressing regional issues. They further identify knowledge gaps and uncertainties where more science and data are needed to support operational decisions. While the overviews provide regional advice, they also relate to specific states of ecosystem components and to specific pressures linked to wider regional drivers such as climate change, global pollution and biodiversity loss, highlighting where these processes have a higher impact.

As part of its communication and dissemination efforts, ICES also develops ecosystem overviews (EOs) infographics. Fig. 2 shows the infographic of the Central Arctic ecosystem highlighting the key signals: human activities and their pressures, the state of the ecosystem, and climate change.

EBM is an iterative process, and hence the ecosystem overviews are in continuous evolution. Since their earliest conception in 2016, this advice has adapted and incorporated new sections following evaluation and feedback from stakeholders and policymakers, and in response to new scientific evidence and methods. A Climate Change section was thus incorporated in 2019 recognizing climate change as a main global driver with effects at a regional scale on ecosystem components (ICES, 2019). This section is in continuous evolution, in collaboration with ICES-PICES Strategic Initiative for Climate Change (SICCME), to account for past and projected climatic changes in the ecoregions, including key variables and the ecosystem components affected.

In addition, two other sections have been introduced in recent years: a Social and Economics section, led by WGSOCIAL and WGECON, linked mostly to fisheries;

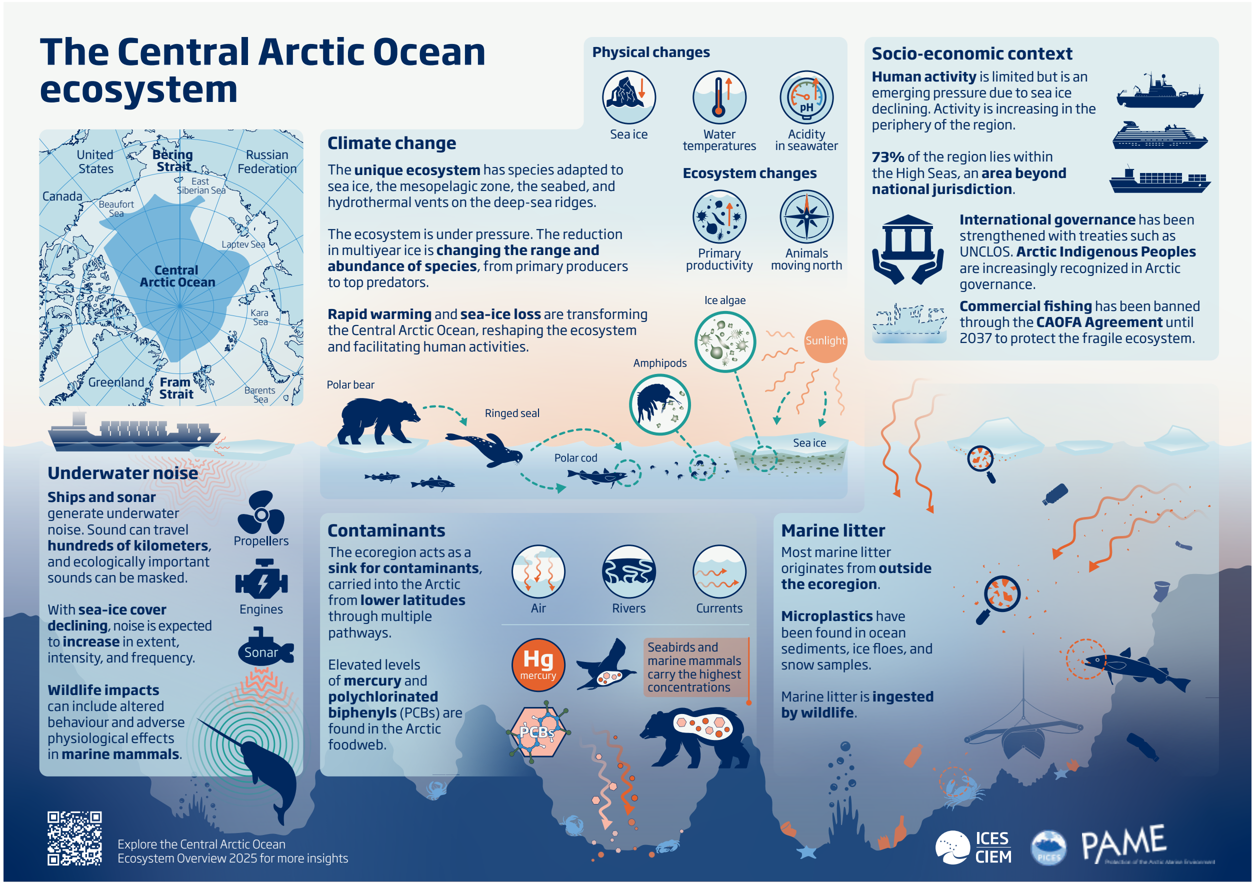


Fig. 2. Infographic of the Central Arctic Ocean ecosystem (ICES, PICES, PAME). (https://www.ices.dk/SiteCollectionImages/ecosystem%20overviews/Central%20Arctic%20Ocean/Ecosystem_Overview_CAO_Infographic_2025.png

and a benthic assessment section (based on the work of WGFBIT (ICES, 2025b), in which specific trade-offs are considered (*i.e.* sea bed impacts from the use of mobile bottom-contacting gear (MBCG) on different seabed habitats and communities (see section 2.3)). In the future, the social and economic section will need to incorporate management objectives and social indicators for other human activities, specifically shipping, as this is one of the other main activities highlighted by several EOs as an important pressure.

The EOs help identify key drivers and risks, and could be used to explore trade-offs between competing fisheries, ecosystem protection, and other human activity management objectives. They are consequently a platform through which different human activities are contextualized in an advice format. The Ecosystem Overviews therefore have a great opportunity ahead as a vector to advance EBM within the ICES community. Their adaptive nature will allow them to have more explicit links with global challenges (*i.e.* climate change, pollution and biodiversity loss) and to strengthen the pillars of sustainability by incorporating quantitative indicators and thresholds linked to operational management objectives. In this way, the overviews will better fulfil their role, moving from a contextual form of advice providing actionable advice linked to decision-makers needs to promote systemic changes in how society interacts with the marine environment.

ICES advice on the impact of ecosystems on fisheries

One of the key fisheries management objectives in the Northeast Atlantic is the Maximum Sustainable Yield (MSY) concept, which aims to maximize long-term exploitation of stocks while remaining precautionary. The ICES MSY approach is based primarily on single-stock assessments, although ecosystem considerations may be incorporated where relevant and supported by available information. For example, ICES advice for North Sea sandeel under the MSY approach explicitly adjusts catch advice based on recent recruitment variability, with reduced catches following consecutive years of low recruitment, thereby implicitly reflecting environmental influences on stock productivity (ICES, 2025d). However, increasing environmental variability and long-term changes driven by climate change are not systematically accounted for within the MSY framework, highlighting the need to better integrate these factors into fisheries management.

Historically, incorporating complex ecosystem information into short-term single-stock fisheries management advice has proven challenging. Multi-species models are complex and often uncertain, and finding environmental drivers with sufficient explanatory power to warrant incorporation into single stock assessment has also proven largely elusive (Trenkel *et al.*, 2023).

In some cases, ICES implicitly integrates these complex environmental drivers into short-term tactical management advice by using recent biological parameters or recruitment assumptions. The ICES Working Group on Multispecies Assessment Methods (WGSAM) develops multispecies models that consider species, food-web and fishery interactions, and multiple sources of uncertainty, including climate change (ICES, 2024g). Multi-species model "key runs" are used to provide dynamic natural mortality-at-age estimates for stocks in the Baltic and North Sea. Outputs from these models are used to provide dynamic natural mortality-at-age estimates for several Baltic and North Sea stocks (Trenkel *et al.*, 2023).

To allow flexibility in TAC setting, ICES introduced the "Pretty Good Yield" (PGY) approach in 2015, using fishing mortality ranges around F_{MSY} (the fishing mortality rate expected to achieve MSY in the longer term), from $F_{MSYlower}$ to $F_{MSYupper}$ (Hilborn, 2010). This approach reflects that yields near MSY can be achieved across a range of fishing pressures, with only minor losses in long-term catch. Fishing within these ranges is considered precautionary and allows managers to balance trade-offs, including mixed-fisheries constraints and ecosystem considerations. However, clear and consistent guidance on how to select values within the range in practice has remained limited, leaving operational decisions largely case-specific.

A more recent tool for directly integrating quantitative environmental drivers is the ecosystem-informed F (F_{ECO}) approach, which uses indicators derived from ecosystem models to adjust the advised target fishing mortality within the predefined F_{MSY} ranges depending on ecosystem condition (Bentley *et al.*, 2021). The ecosystem-based fishing mortality reference point ($F_{ECO)}$ approach) was co-developed during a series of ICES workshops known as WKIrish, focused on the Irish Sea (ICES division VIIa). WKIrish brought together scientists, stakeholders, policy advisors, and environmental non-governmental organizations (eNGOs) to align research objectives with policy needs, engage early and often with stakeholders, apply best practice in model development and ultimately co-design and operationalize EAFM. F_{ECO} utilizes ecosystem indicators to select a target fishing mortality within these established ranges (Bentley *et al.*, 2021). F_{ECO} is defined as a precautionary reference point that varies dynamically based on the strategic understanding derived from ecosystem models, scaling fishing mortality down when ecosystem conditions are poor for a specific stock, and up when conditions are favorable, while maintaining the integrity of ICES precautionary rules. The F_{ECO} concept allows for the integration of multiple indicators by using weighting factors to estimate an overall indicator status for a stock.

The concept does not require replacing standard assessment methodologies, thus maintaining the robustness of existing models for short-term forecasting. While currently limited in application to data-rich stocks with existing F_{MSY} advice, F_{ECO} offers a pragmatic and transparent stepping-stone for incorporating ecosystem information into tactical fisheries advice, accelerating progress towards Ecosystem-Based Fisheries Management (EBFM).

In a recent paper, Trenkel *et al.* (2023) presented a comprehensive audit of how ecosystem trends and variability (ETV) are currently incorporated into ICES fishing opportunities advice in the Northeast Atlantic . This analysis covered 87% of stocks, representing 99% of total landings, and showed that ETV was incorporated in at least one way (tactical or strategic advice) for nearly three-quarters (73%) of the stocks that responded to the audit. The inclusion of ETV is often implicit, driven by a general commitment to use the "best available science" rather than explicit, systematic instruction. For example, environmental drivers such as sea surface temperature influencing recruitment are commonly accounted for through recruitment estimates and short-term forecasts, while trophic processes are reflected through the incorporation of time-varying natural mortality driven by predation in multispecies assessments. While ETV is widely considered, only 46% of the stock assessments included it quantitatively. The authors conclude that while the commitment to use "best available science" has led to significant implicit inclusion of ETV in ICES advice, accelerating progress toward EBFM requires a shift from implicit to explicit instructions, with routine documentation of ecosystem information throughout the advice cycle.

Fisheries impacts on ecosystems: spatial advice and trade-offs

The recognition that fishing activities create complex spatial impacts across marine ecosystems has driven ICES to develop approaches for understanding and quantifying these effects, with particular emphasis on trade-off analyses between the extent of disturbance to seabed habitats from mobile bottom-contacting gear (MBCG) and potential costs to fisheries. ICES's approach to assessing fisheries impacts on ecosystems encompasses both the immediate physical disturbance to seabed habitats and the broader ecological consequences, including bycatch of protected species, impacts on vulnerable marine ecosystems (VMEs), and alterations to marine food webs.

Underpinning ICES spatial assessments is the work of its Working Group on Spatial Fisheries Data (WGSFD), which serves as the primary conduit for ingesting highly resolved fisheries effort data. Through its annual "VMS (Vessel Monitoring System) and Logbooks Data Call", WGSFD compiles spatially explicit fishing activity data from ICES Member Countries, providing the empirical foundation for assessing fishing pressure at fine spatial scales. The data call requests anonymized and gridded VMS data, linked to logbook records of gear codes and vessel parameters (length and power), enabling calculation of swept area and swept-area ratio (SAR) at fine scales for MBCGs, as well as associated catch weights and values. This standardized approach to spatial data collection and quality control ensures that fishing intensity estimates are comparable across regions and consistent over time. WGSFD's ongoing methodological development addresses challenges such as differentiating fishing from non-fishing activity based on vessel speed, allocating landings weight and value to spatial locations, and estimating gear dimensions for swept area calculations.

The Working Group on Fisheries Benthic Impact and Trade-offs (WGFBIT) is ICES's primary forum for developing methods and assessments to evaluate the benthic impact of fisheries at regional scales while considering trade-offs between fisheries and seabed health. The group has developed a quantitative Europe-wide assessment of bottom-trawl impacts across the Baltic, Atlantic, Mediterranean, and Black Seas. This approach utilises two key indicators of seabed status: RBS_{tot} (biomass relative to fauna carrying capacity) and RBS_{sen} (biomass of the 10% most sensitive fauna relative to carrying capacity), enabling scientists to identify significant regional and habitat differences in bottom-trawling impacts (ICES, 2025a).

ICES's approach incorporates methodological frameworks for assessing significant adverse effects on seabed habitats and has developed evaluation criteria for both state-based and pressure-based indicators. It applies systematic approaches to threshold setting, distinguishing between qualitative risk assessments suitable for data-limited circumstances and quantitative assessments requiring extensive monitoring data. This framework enables ICES to provide regionally appropriate advice while maintaining scientific rigour across different data-availability scenarios (ICES, 2022a).

The spatial dimension of ICES's benthic impact assessments has evolved considerably, moving from simple pressure mapping to sophisticated models that account for habitat sensitivity, recovery rates, and cumulative effects. The methodology developed by WGFBIT estimates the relative decline in biomass of the most vulnerable community components, with indicators designed to be responsive to gradients of trawling pressure while maintaining comparability across different regions and assessment methods. This approach has enabled ICES to provide spatially explicit advice on where fishing activities are likely to cause the greatest ecosystem impacts and where protective measures might be most effectively implemented. This advice examined mobile bottom-contacting gear (MBCG) fisheries and revealed that fishing activities are spatially aggregated into core areas accounting for most of the landings value, and peripheral areas of relatively low economic importance. On average, 90% of MBCG landings value originates from less than 50% of the fished area when evaluated at 0.05° grid cells (ICES, 2024a).

The analysis demonstrated that maintaining a persistently unfished state in 50% of all Marine Strategy Framework Directive Broad Habitat Types within the Greater North Sea and Celtic Seas would reduce annual mean MBCG landings value by approximately 20%. More stringent protection levels showed steeper trade-offs, with 70% habitat protection associated with landings value reductions of 31.6% and 36.7% per year in these two regions, respectively. The Baltic Sea, however, demonstrated a different set of trade-off relationships, with maintaining 70% of habitats in an unfished state resulting in a reduction of less than 7% of annual mean MBCG landings value, reflecting the existing limited distribution of bottom-contacting fishing activities there (ICES, 2024a).

These analyses reveal the spatial heterogeneity of fishing pressure and economic dependency. Core fishing grounds (defined as the smallest area yielding 90% of landings value) exhibit temporal variability, with fewer than 50% of c-squares[1] fished by individual métiers being classified as core fishing grounds in every year during 2017–2022, in the EU waters of the Greater North Sea and Celtic Seas areas. This temporal instability has important implications for spatial management measures, suggesting that fixed area closures may not consistently protect the most economically valuable fishing grounds.

The theoretical foundations underpinning ICES's trade-off approaches draw on optimisation models demonstrating that biodiversity protection and sustainable harvest can often be achieved simultaneously when important biodiversity components are spatially isolated or differentially affected by various fishing gears. Research suggests that roughly 80% of potential harvestable yield can be maintained while protecting 70% of biodiversity when spatial and gear-based management strategies are effectively implemented (Hilborn *et al.*, 2020).

ICES's work on vulnerable marine ecosystems (VMEs) exemplifies the organisation's evolving spatial approach to protecting ecosystem components that are particularly vulnerable to fishing impacts. The advice on areas

1 a c-square (concise spatial query and representation system) is a standardized geographical grid system used to divide the ocean into equal-sized spatial units for mapping and data analysis. https://doi.org/10.5670/oceanog.2003.52

where VMEs are known or likely to occur in EU waters (ICES, 2024b) demonstrates the evolution of spatial management from simple area closures to sophisticated risk-based approaches. ICES presented five spatial management scenarios based on updated information on VME occurrence and the distribution of MBCG fishing activity, providing advice requesters with options covering a range of risk tolerances, and resulting in VME protection polygons ranging from 102–115 in number and covering 9,752–14,885 km² in total area. This evidence-based procedure for producing recurrent ICES advice on VME was benchmarked in 2022 (ICES, 2022b).

The organisation's approach to providing advice on VME protection extends beyond EU waters to the North-East Atlantic Fisheries Commission (NEAFC) regulatory areas, where ICES has evaluated the biodiversity attributes of restricted bottom fishing areas. Each of the 14 polygons identified in NEAFC Regulatory Areas 1 and 2 contains multiple biodiversity attributes as articulated in Convention on Biological Diversity guidance, including communities of rare, threatened or endangered species, representative natural ecosystems, and areas providing critical ecosystem functions. This work demonstrates how ICES translates international biodiversity criteria into operational spatial management advice (ICES, 2024c).

The spatial dimension of bycatch impacts (ICES, 2024d) represents another critical area where ICES provides ecosystem-focused advice. Recent analysis of static net fisheries revealed complex spatial patterns in marine mammal bycatch, with acoustic deterrent devices (ADDs) showing effectiveness in reducing harbour porpoise bycatch to 0.23 of background rates, while simultaneously increasing seal bycatch rates by a factor of 2.43 (ICES, 2024e). These findings highlight the spatial heterogeneity in the effectiveness of mitigation measures, the need for location-specific management approaches, and the recognition that such measures may relocate problems spatially or temporally rather than solving them.

Contemporary ICES work increasingly focuses on fishing displacement effects caused by emerging human activities, such as offshore renewable energy developments and marine protected areas, using spatial effort and catch data to identify critical fishing areas and analyse catch rates of key commercial species. This research provides essential information for understanding how spatial restrictions in one area may intensify impacts in others, supporting marine spatial planning (MSP) and more holistic ecosystem-based management approaches.

Implementation pathways for EAFM

ICES plays a central role as an advice provider for fisheries management organizations adopting an EAFM. A recent example is ICES advice to NEAFC outlining ecosystem-based approaches to fisheries management (ICES, 2024a). In this advice, ICES detailed five distinct methods ranging from low to high complexity and data needs (ICES, 2024f). ICES advised that operational ecological objectives for EAFM should span six core ecological issues: target species; bycatch species or groups; discards; Endangered, Threatened, and Protected (ETP) species; benthic habitat impacts; and ecosystem structure and function impacts. The process for setting these operational objectives should be inclusive, consultative, and evidence-informed, based on a shared understanding between managers, scientists, and stakeholders. These objectives must be clearly linked to existing or potential management actions within the managing authority's competence.

The five approaches to EAFM implementation

The five approaches described—Qualitative Risk Assessment (RA), Semi-quantitative RA, Ecosystem Status Indicators Framing Fisheries Decision-Making (ESI), Northwest Atlantic Fisheries Organization (NAFO) EAF Roadmap, and the Marine Strategy Framework Directive (MSFD)—were compared based on their requirements, maturity, and contribution to EAFM (ICES, 2024e).

1. Qualitative Risk Assessment (Qualitative RA): This approach is used when the evidence base is sparse or highly uncertain. It is a quick assessment method, often applied as an initial screen, that can address almost all EAFM issues. It uses expert opinion to provide general guidance on management actions. Monitoring requirements are low to medium, and it can be applied even when data are very limited. However, adequate precautions must be applied to offset significant assumptions, which may cause concern among stakeholders and regulators.

2. Semi-quantitative Risk Assessment (Semi-quantitative RA): This requires some quantitative data and provides risk estimates with greater formality than Qualitative RA. Its outputs can lead to precise advice on management actions and may estimate absolute risk and attribution between fleets, strengthening the link to decision-making. It has medium, variable data needs, and monitoring requirements are often met by existing data.

3. Ecosystem Status Indicators Framing Fisheries Decision-Making (ESI): This approach supplements existing decision processes by using a broad range of data types to provide ecosystem context. Information is often delivered via risk tables to improve consistency in decision-making. While the approach provides a system-scale view and is easily integrated with existing processes, its link to management is informal and dependent on the willingness of decision-makers to use the information, as there is no formal quantitative link to decision rules.

4. NAFO Ecosystem Approach to Fisheries (NAFO EAF) Roadmap: This approach is relatively resource-intensive and addresses a subset of EAFM issues, including targets for Vulnerable Marine Ecosystems (VMEs), biodiversity, and ecosystem overfishing. It explicitly links objectives to indicators and targets. Its monitoring needs are medium-high, relying on extensive annual scientific trawl surveys.

5. Marine Strategy Framework Directive (MSFD): This is the most data- and resource-intensive approach, applied in EU marine waters, involving detailed monitoring and assessment across eleven descriptors. It informs decision-making by tracking trends in ecosystem components and pressures (EU, 2008). However, the set of targets remains incomplete, and its efficacy is challenged by the lack of a clear, direct link between its requirements and the management actions taken through the Common Fisheries Policy (EU, 2002).

Implementation and Challenges

All five approaches inform management and, in most cases, lead to management actions related to ecological well-being. Importantly, the implementation of EAFM can be incremental, often using risk assessments to screen issues and define priorities for more resource-demanding methods. However, methods to assess ecosystem structure and function impacts are still in the early stages of development across jurisdictions. Furthermore, while most approaches can address ecological aspects, non-ecological requirements like social and economic performance are generally not thoroughly considered or directly addressed.

FEISA as an integrating framework

The ICES Framework for Ecosystem-Informed Science and Advice (FEISA; Roux and Pedreschi, 2024) provides the framework needed to support Ecosystem-Based Management (EBM).

The rationale for EBM and FEISA

Conventional siloed approaches to resource management (single-sector/single-species) have proven ineffective for achieving long-term sustainability goals, and there is a need to apply a systems-thinking approach to understand and manage interconnected socio-ecological systems. However, operationalizing EBM is challenging due to inherent complexity, resource and capacity limitations, and significant data and knowledge gaps, especially concerning social and economic data.

FEISA's architecture: indicators and risk

FEISA addresses these challenges by combining two core building blocks to translate knowledge into evidence for advice, namely a system of indicators and a risk-based approach (Fig 3):

1. A System of Indicators: Indicators are measurable information on the socio-ecological systems. They must be relevant to the full spectrum of EBM objectives, including marine ecosystems, individual components, human activities/pressures (including climate change),

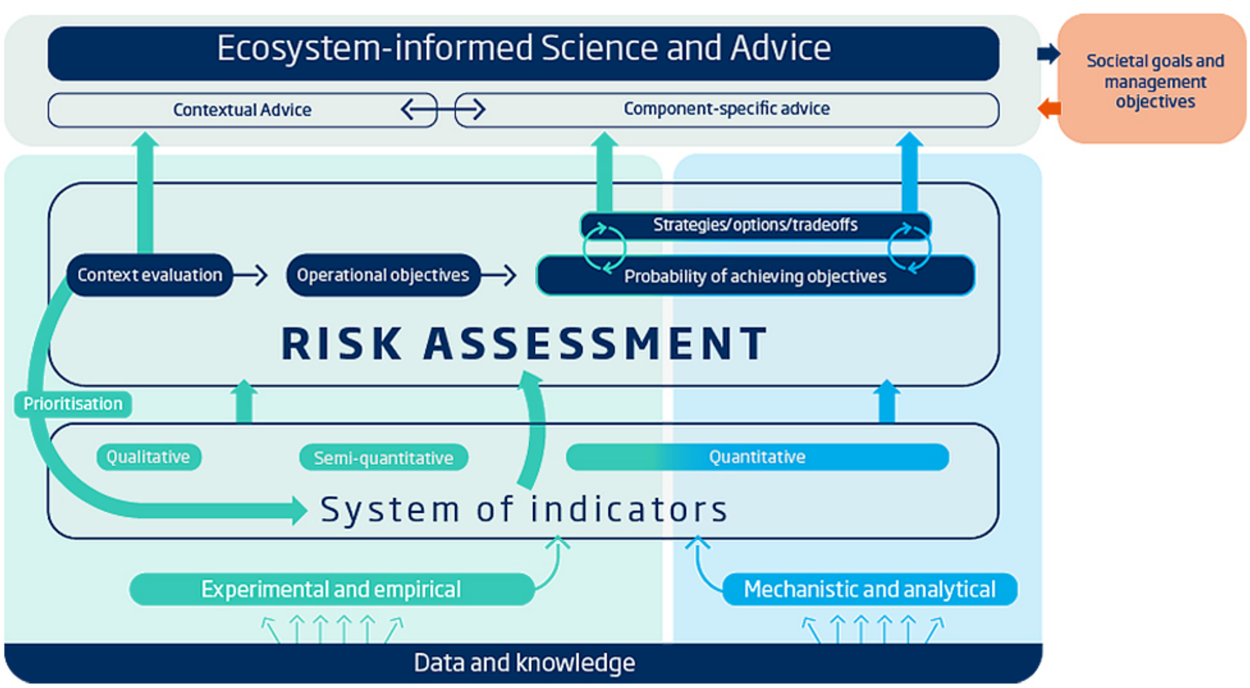


Fig. 3. ICES Framework for Ecosystem-Informed Science and Advice (FEISA). See description in text.

and social, cultural, and economic well-being. Indicators can be qualitative, semi-quantitative, or quantitative. To be operational, indicators must be linked to operational objectives—specific values or ranges (*e.g.*, baselines, limits) used to track status, trends, and risk. These differ from management objectives, which are long-term aspirational goals set by governing bodies.

2. A Risk-Based Approach: Risk provides a common currency for merging different types of indicators and formally treating consequences and uncertainties. This approach aligns with the widely adopted precautionary principle. FEISA uses two types of risk assessment:

- **Context-based risk assessments:** Used primarily for risk identification and prioritization of human activities, pressures, and components within the broader socio-ecological context (e.g., in ICES Ecosystem Overviews (EOs)). These often rely on experiential and empirical evidence.

- **Objective-based risk assessments:** Used to probabilistically evaluate the potential outcomes, consequences, and trade-offs of alternative management options against operational objectives. These require explicit specification of objectives and are standard practice in fisheries advice (*e.g.*, evaluating the probability of breaching biological limits).

Discussion

The examples reviewed in this paper show that ICES is moving from largely single-stock and sector-specific advice towards a more integrated, ecosystem-informed advisory system. Ecosystem Overviews provide regional context and identify priority pressures (ICES, 2023a; ICES, 2025c); ecosystem-informed stock advice incorporates environmental variability and multispecies interactions into fisheries advice (Trenkel *et al.*, 2023; Bentley *et al.*, 2021); spatial assessments quantify fisheries impacts and trade-offs (ICES, 2024a; ICES, 2024b; ICES, 2024c; ICES, 2024d; ICES, 2024e); and implementation guidance supports managers in selecting approaches suited to available data, resources, and objectives (ICES, 2024f). Taken together, these products form a layered advisory pathway for operationalizing EAFM in the Northeast Atlantic.

FEISA provides the conceptual and operational architecture for connecting these products. Its emphasis on indicators, risk assessment, uncertainty, and incremental implementation allows ecosystem information to be incorporated across a wide range of advice contexts, from data-limited qualitative assessments to quantitative evaluations of management options (Roux and Pedreschi, 2024). This is important because EAFM does not require perfect information before action can be taken; rather, it requires transparent use of available knowledge, explicit treatment of uncertainty, and clear links between scientific advice and management objectives.

Nevertheless, the transition from ecosystem-informed science to operational management remains incomplete. Many ecosystem considerations are already included in ICES advice, but often implicitly or case by case rather than through systematic instructions and routine documentation. In addition, ICES advice can identify risks, trade-offs, and management options, but implementation depends on whether management authorities define operational objectives, clarify acceptable levels of risk, and establish processes for translating advice into action (ICES, 2024e; Garcia *et al.*, 2014).

Transitioning to ecosystem-based fisheries management (EAFM) requires balancing biological, ecological, economic, and social objectives, supported by effective dialogue among policymakers, managers, scientists, and stakeholders. Progress remains constrained by institutional readiness, capacity limitations, and gaps in socio-economic data, alongside differing expectations on the role of ICES advice in integrating human dimensions.

Achieving ecosystem objectives is further challenged by fragmented governance and limited formal processes for integrating ecosystem considerations into fisheries management, as well as by misalignments between key policy frameworks such as the Common Fisheries Policy (EU, 2013), the Marine Strategy Framework Directive (EU, 2008), the Maritime Spatial Planning Directive (EU, 2014), and the Nature Restoration Regulation (EU, 2024).

Governance systems and management instruments (*e.g.* TACs, technical measures, and effort controls) shape not only ecological outcomes but also the social and economic sustainability of fisheries and dependent communities (Garcia *et al.*, 2014).

In this context, ICES has developed integrative approaches to support the transition towards EAFM, notably through the Framework for Ecosystem-Informed Science and Advice (FEISA), which provides a structured and iterative way to incorporate diverse knowledge types into ecosystem-based advice (Roux and Pedreschi, 2024; ICES, 2024).

Integration and synthesis of ICES's EAFM framework

The Framework for Ecosystem Informed Science and Advice (FEISA) represents an operational basis through which ICES can translate complex ecosystem science into actionable management advice.

The common theme unifying the examples given above is FEISA's capacity to incorporate diverse forms of knowledge and multiple levels of data availability. The Ecosystem Overviews, for example, highlight

FEISA's context-based risk management approach, using both quantitative data and expert judgement to identify and prioritize regional pressures. This mixed methodology has proven particularly valuable in data-limited scenarios, allowing ICES to provide meaningful advice whilst explicitly acknowledging uncertainties. Similarly, the F_{ECO} approach demonstrates how FEISA's indicator-based system can operationalize ecosystem information within existing single-species frameworks, maintaining precautionary management while enhancing responsiveness to ecosystem conditions.

What distinguishes FEISA from previous frameworks is its pragmatic acceptance that perfect information is neither achievable nor necessary for effective management. By establishing a common approach to risk, FEISA enables the integration of different information sources – from VMS positional data to stakeholder sentiment – into coherent advice products. This flexibility is important as ICES moves to address increasingly complex questions involving multiple objectives, sectors, and scales.

FEISA supports incremental implementation, allowing progression from qualitative risk assessments in data-limited situations to more quantitative analyses as information availability improves. This graduated approach removes the artificial barrier between 'data-poor' and 'data-rich' contexts, enabling all regions and stocks to benefit from ecosystem considerations regardless of their current monitoring capacity. Ultimately, FEISA provides the structure needed to promote knowledge plurality and the routine exploration of alternative hypotheses and scenarios, ensuring advice is better aligned with societal drivers and ecosystem-based management goals.

The trade-off analyses developed by WGFBIT exemplify FEISA's objective-based risk assessment in practice, evaluating the consequences of management scenarios against explicit operational objectives. These analyses move beyond simple impact assessments to quantify the relationships between different activities and ecosystem protection, providing decision-makers with the evidence base needed to navigate the political choices around resource allocation and conservation priorities.

Implementation

While ICES has demonstrated several operational assessments and examples that provide advice according to EBFM principles, these assessments are often project-based and frequently constrained by time, budget, or data availability. ICES's Framework for Ecosystem-Informed Science and Advice (FEISA) provides the overarching structure within which spatial fisheries impact assessments are integrated with broader ecosystem considerations. The framework mobilizes different types of data and knowledge to define measurable indicators, which are then integrated into advice via both context-based and objective-based risk assessments. This ensures that spatial analysis of fisheries impacts contributes to comprehensive ecosystem assessments rather than remaining isolated technical exercises.

The evolution of ICES's spatial approach to fisheries ecosystem impacts reflects both advancing scientific understanding and growing policy demands for quantitative trade-off analyses. By combining sophisticated modelling approaches with pragmatic consideration of implementation challenges, ICES continues to refine its capacity to provide actionable advice on balancing fishing activities with ecosystem protection across the complex spatial mosaic of Northeast Atlantic marine systems.

Remaining challenges and limitations

ICES has made significant progress in obtaining and analyzing VMS and logbook data, which now underpin much of its spatial analysis. These data have inherent limitations linked to the scale at which impacts can be interpreted, challenges in inferring fishing activity and legal hurdles in sharing and presenting outputs. Spatial data on other human activities at sea remain limited and restricted, hampering comprehensive assessment of cumulative impacts and interactions between sectors. Social and economic data lag even further behind, creating imbalanced assessments that may inadequately capture the bigger picture. Climate and environmental modelling, while improving, still show temporal and spatial gaps that limit the precision at which ecosystem change can be monitored and interpreted.

EAFM assumes coordinated management actions across sectors and jurisdictions, yet governance structures remain predominantly sectoral and national. ICES can provide integrated scientific advice but translating that advice into coherent management actions requires institutional arrangements that may not exist. The divide between the spatial scales at which ecosystems function and the administrative boundaries through which they are governed creates persistent challenges for implementing ecosystem-based management.

Resource limitations constrain what is possible. Comprehensive assessment of ecosystems is resource-intensive and costly, requiring specialist expertise, extensive data collection, sophisticated analytical capabilities, and sustained political commitment. As advice demands grow to cover more ecosystem components, human activities, and management questions, there is a risk of overextending available resources, compromising the quality of advice, or limiting ICES's capacity to respond to other priorities.

Future directions and priorities

While Trenkel *et al.* (2023) demonstrated that ecosystem trends and variability are already widely incorporated into ICES advice, their analysis revealed that much of this integration remains implicit rather than systematic. The transition to a systematic integration represents the next critical step in ecosystem-based advice, requiring both methodological changes and institutional commitment to standardized approaches for incorporating ecosystem information explicitly across advice products. The FECO concept provides a template for this transition, showing how ecosystem indicators can be integrated into advice, while maintaining existing advisory frameworks (Bentley *et al.*, 2021). Extending such approaches beyond data-rich stocks presents both technical and resourcing challenges.

Current EAFM implementation has made substantial progress on ecological dimensions but remains comparatively underdeveloped in systematically addressing social and economic considerations beyond fisheries. The recent incorporation of social and economic sections into the ICES Ecosystem Overviews represents a first step, but comprehensive operationalization requires expanding this work to other marine sectors.

Future development requires advice requesters and managers to establish operational social and economic objectives, with associated indicators and thresholds, comparable to those now routine for ecological components. ICES can provide the scientific framework and methodological guidance to support such objectives, but their definition and prioritization must be co-developed with management bodies. This is particularly pressing for sectors like shipping, which the Ecosystem Overviews identify as a major regional activity, yet for which management objectives and social indicators remain largely undefined. Collaborative dialogue between ICES and its advisory requesters will be essential to clarify what questions need answering and what operational objectives are required to support cross-sectoral management decisions.

Broader policy context and implications

ICES's EAFM development has not occurred in isolation, but in response to the evolving policy landscape at both global and regional scales. The UN Decade of Ocean Science for Sustainable Development (2021-2030) and the post-2020 Global Biodiversity Framework, with its target of effectively conserving 30% of marine areas by 2030, create a context in which ecosystem-based approaches shift from aspirational to essential.

At the regional level, the European Union's interlinked policy frameworks- the Common Fisheries Policy, Marine Strategy Framework Directive, Maritime Spatial Planning Directive, and emerging initiatives on offshore renewable energy - demand integrated scientific advice that can address interactions among objectives and sectors. ICES's development of tools such as the Ecosystem Overviews and trade-off analyses directly responds to these policy drivers, providing the evidence base needed for decisions that must simultaneously address biodiversity conservation, food security, climate mitigation, and economic development.

The NEAFC advice on EAFM implementation approaches illustrates how ICES translates these broad policy commitments into operational guidance suited to different institutional contexts and resource availabilities. By describing a continuum of approaches from qualitative risk assessment to comprehensive frameworks like the MSFD, ICES acknowledges that EAFM implementation must be pragmatic and incremental, adapted to the specific circumstances and capacities of different management jurisdictions.

However, this policy landscape also creates tensions. The proliferation of sectoral and environmental legislation fragments governance, creating situations where policies pull in different directions or where cumulative requirements exceed available monitoring and assessment resources. ICES's integrative approach, embodied in FEISA and the Ecosystem Overviews, offers a potential antidote to such fragmentation. Realizing this potential requires policy-makers to actively use integrated advice products in decision-making and that governance structures to evolve in support of cross-sectoral coordination.

Conclusions and Key Messages

The Northeast Atlantic provides an important example of how ecosystem-informed fisheries advice can be developed within a complex ecological, environmental, and governance landscape. The ICES products reviewed in this paper show that EAFM is being operationalized through a layered advisory pathway: Ecosystem Overviews provide regional context and identify priority pressures; ecosystem-informed fisheries advice incorporates environmental variability and multispecies interactions into stock advice; spatial assessments quantify fisheries impacts and trade-offs; and implementation guidance supports management organizations in selecting approaches suited to their objectives, data availability, and capacity.

FEISA provides a unifying framework for this work by connecting these products across different levels of data, information, analytical complexity, and risk. FEISA's value lies not in requiring a single comprehensive model of the ecosystem, but in linking indicators, risk assessment, and uncertainty to the transparent and incremental use of available knowledge, from qualitative expert judgement to quantitative evaluation of management options. This makes it particularly useful for moving ecosystem information from contextual assessment towards more operational advice.

Important challenges remain. Many ecosystem considerations are still incorporated implicitly or case by case rather than through systematic procedures, and implementation depends on management authorities defining operational objectives, acceptable levels of risk, and mechanisms for translating advice into action. Social and economic dimensions also remain less developed than ecological components, particularly beyond fisheries. Strengthening EAFM will therefore require clearer links between science and management objectives, sustained investment in data and capacity, improved treatment of human dimensions, and continued development of advice products that are transparent, risk-based, and actionable.

Overall, the ICES experience demonstrates that operationalizing EAFM is not a single methodological shift, but a gradual reconfiguration of the advisory system. For regional fisheries management organizations and other management bodies, the key lesson is that ecosystem-informed advice can be developed incrementally, provided that scientific products are linked to explicit objectives, uncertainty is communicated transparently, and governance systems are able to act on integrated advice.

References

Bentley, J. W., Lundy, M. G., Howell, D., Beggs, S. E., Bundy, A., de Castro, F., Fox, C. J., Heymans, J. J., Lynam, C. P., Pedreschi, D., Schuchert, P., Serpetti, N. Woodlock, J., and Reid, D. G. 2021. Refining Fisheries Advice With Stock-Specific Ecosystem Information *Front. Mar. Sci.*, 08 April 2021. Sec. *Marine Fisheries, Aquaculture and Living Resources*.**Volume 8** - 2021. https://doi.org/10.3389/fmars.2021.602072

European Union. 2002. Council Regulation (EC) No 2371/2002 of 20 December 2002 on the conservation and sustainable exploitation of fisheries resources under the Common Fisheries Policy.

European Union. 2008. Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for Community action in the field of marine environmental policy (Marine Strategy Framework Directive). *Official Journal of the European Union*, **L 164**, 19–40.

European Union. 2013. Regulation (EU) No 1380/2013 of the European Parliament and of the Council of 11 December 2013 on the Common Fisheries Policy, amending Council Regulations (EC) No 1954/2003 and (EC) No 1224/2009 and repealing Council Regulations (EC) No 2371/2002 and (EC) No 639/2004 and Council Decision 2004/585/EC. *Official Journal of the European Union*, **L 354**, 22–61.

European Union. 2014. Directive 2014/89/EU of the European Parliament and of the Council of 23 July 2014 establishing a framework for maritime spatial planning. *Official Journal of the European Union*, **L 257**, 135–145.

European Union. 2024. Regulation (EU) 2024/1991 of the European Parliament and of the Council of 24 June 2024 on nature restoration and amending Regulation (EU) 2022/869. Official Journal of the European Union, L 2024/1991.

FAO. 2021**.** Ecosystem approach to fisheries implementation monitoring tool – A tool to monitor implementation of the ecosystem approach to fisheries (EAF) management. User manual. Rome. https://doi.org/10.4060/cb3669en

FAO. 2003. Fisheries management. 2. The ecosystem approach to fisheries. *FAO Technical Guidelines for Responsible Fisheries* No. 4, Suppl. 2. FAO, Rome. 112 p.

FAO. 2021. *FAO publications series 2021: fisheries and aquaculture.* FAO, Rome.

Garcia, S. M., Rice, J. C., and Charles, A. (Eds.). 2014. Governance of Marine Fisheries and Biodiversity Conservation: Interaction and Coevolution. Chichester, UK: Wiley-Blackwell https://doi.org/10.1016/j.marpol.2009.04.013

Hilborn, R. 2010**.** Pretty Good Yield and exploited fishes. *Marine Policy*, **34(1)**, 193–196.

Hilborn, R., Akselrud, C. A., Peterson, H., and Whitehouse, G. A. 2020**.** The trade-off between biodiversity and sustainable fish harvest with area-based management. *ICES Journal of Marine Science*. https://doi.org/10.1093/icesjms/fsaa139

ICES. 2019**.** Workshop on the design and scope of the 3rd generation of ICES Ecosystem Overviews (WKEO3). *ICES Scientific Reports*, **1:40**. https://doi.org/10.17895/ices.pub.5445

ICES. 2021. Workshop on methods and guidelines to link human activities, pressures and state of the ecosystem in Ecosystem Overviews (WKTRANSPARENT; outputs from 2020 meeting). *ICES Scientific Reports*. **3:17**. 59 p. https://doi.org/10.17895/ices.pub.7930

ICES. 2022a. EU request to advise on methods for assessing adverse effects on seabed habitats" *ICES Advice* 2022, sr.2022.18

ICES. 2022b**.** Benchmark Workshop on the occurrence and protection of VMEs (vulnerable marine ecosystems) (WKVMEBM). *ICES Scientific Reports*. **4:55**. 99 p. https://doi.org/10.17895/ices.pub.20101637

ICES. 2023a. ICES Ecosystem Overviews Technical Guidelines, Version 4. *ICES Advice Technical Guidelines.* Copenhagen: International Council for the Exploration of the Sea. https://doi.org/10.17895/ices.pub.22059803

ICES, 2023b. Guide to ICES advisory framework and principles. General ICES Advice guidelines. Report. https://doi.org/10.17895/ices.advice.22116890.v1

ICES. 2023c. Advice on fishing opportunities, catch, and effort. *ICES Advice* 2023. Copenhagen: International Council for the Exploration of the Sea. Available at: https://doi.org/10.17895/ices.advice.22240624

ICES. 2024a. EU request on spatial trade-off analysis between reducing the extent of mobile bottom-contacting gear (MBCG) disturbance to seabed habitats and potential costs to fisheries. *In* Report of the ICES Advisory Committee, 2024. *ICES Advice* 2024, sr.2024.05, https://doi.org/10.17895/ices.advice.25601121

ICES. 2024b. Advice on areas where Vulnerable Marine Ecosystems (VMEs) are known to occur or are likely to occur in EU waters. *In* Report of the ICES Advisory Committee, 2024. *ICES Advice* 2024, **vme.eu**. https://doi.org/10.17895/ices.advice.26983726.

ICES. 2024c. NEAFC request on whether ICES advice of 2023, on the long-term biodiversity/ecosystem benefits of

NEAFC's restricted bottom fishing areas, also applies to 14 defined polygons in NEAFC Regulatory Area (RA) 1 and RA 2. *In* Report of the ICES Advisory Committee, 2024. *ICES Advice* 2024, **sr.2024.16**. https://doi.org/10.17895/ices.advice.27101086.

ICES. 2024d. Bycatch of endangered, threatened and protected species of marine mammals, seabirds and marine turtles, and selected fish species of bycatch relevance. *In* Report of the ICES Advisory Committee, 2024. *ICES Advice* 2024, byc.eu. https://doi.org/10.17895/ices.advice.27999401

ICES. 2024e. EU request on alternative measures to prevent bycatch of the harbour porpoise (*Phocoena phocoena*) in the Baltic Sea. *In* Report of the ICES Advisory Committee, 2024. *ICES Advice* 2024, sr.2024.12. https://doi.org/10.17895/ices.advice.26868907

ICES. 2024f**.** NEAFC request on Ecosystem Approaches to Fisheries Management. *In* Report of the ICES Advisory Committee, 2024. *ICES Advice* 2024, **sr.2024.13**. https://doi.org/10.17895/ices.advice.27052372.

ICES. 2024g. Working Group on Multispecies Assessment Methods (WGSAM)*. ICES Scientific Reports*, **6:99**. 77 p. https://doi.org/10.17895/ices.pub.27919473

ICES. 2025a**.** Working Group on Mixed Fisheries Advice (WGMIXFISHADVICE; outputs from 2024 meeting). *ICES Scientific Report.* Copenhagen: ICES. https://doi.org/10.17895/ices.pub.28182638

ICES. 2025b. Working Group on Fisheries Benthic Impact and Trade-offs (WGFBIT; outputs from 2024 meeting). *ICES Scientific Reports*. **7:18**. 90 p. https://doi.org/10.17895/ices.pub.28351412

ICES. 2025c. Oceanic Northeast Atlantic – Ecosystem Overview. *ICES Advice*: Ecosystem Overviews. Report. https://doi.org/10.17895/ices.advice.30597185.v1

ICES. 2025d**.** Sandeel (*Ammodytes* spp.) in divisions 4.b–c, Sandeel Area 1r (central and southern North Sea, Dogger Bank). *In*: Report of the ICES Advisory Committee*,* 2025. *ICES Advice* 2025, san.sa.1r. https://doi.org/10.17895/ices.advice.27202845

Pedreschi, D., Niiranen, S., Skern-Mauritzen M., and Reid, D. G. 2023. Operationalising ODEMM risk assessment for Integrated Ecosystem Assessment scoping: Complexity vs. manageability. *Frontiers in Marine Science*, **9**, 1037878. https://doi.org/10.3389/fmars.2022.1037878

Roux and Pedresch. 2024. ICES Framework for Ecosystem-Informed Science and Advice (FEISA). *ICES Cooperative Research Reports (CRR)*. Report. https://doi.org/10.17895/ices.pub.25266790.v1

Trenkel, V. M., Ojaveer, H., Miller, D. C. M., and Dickey-Collas, M. 2023. The rationale for heterogeneous inclusion of ecosystem trends and variability in ICES fishing opportunities advice. *Marine Ecology Progress Series*, 704, 81–97. https://doi.org/10.3354/meps14227

Scientific Publications of the Northwest Atlantic Fisheries Organization

In efforts to reduce paper usage and ensure publications are accessible to all, publications are available FREE electronically at *www.nafo.int* or *https://journal.nafo.int*

The NAFO publications listed below are available through the NAFO Secretariat.
Prices include postage and handling.

Please note: Pricing for volumes shipped outside of Canada is higher due to increased postage costs.

	Price Canada (CAD $)	Price Int'l (CAD $)
Early Stages of Fishes in the Western North Atlantic Ocean (Davis Strait, Southern Greenland and Flemish Cap to Cape Hatteras) - 2007		
This comprehensive scientific publication is the only up-to-date textbook providing detailed descriptions and accurate drawings of the early life-history stages of the fishes from the Northwest Atlantic Ocean north of 35°N and west of 40°W. The region covers the world's most famous fishing grounds and includes the Davis Strait, southern Greenland, Flemish Cap, Georges Bank, northern Sargasso Sea and Middle Atlantic Bight to Cape Hatteras.		
Available online only; hardcover volume set is sold out.		
Identification Guides		
Coral, Sponge, and Other Vulnerable Marine Ecosystem Indicator Identification Guide, NAFO Area - 2015. (A pictorial Identification Guide for some species of Coral, Sponge, and other indicator species produced in full-colour on water-resistant paper and bound in a water-proof binder, with tab separators. Additions can be easily added)	30.00	35.00
Sponge Identification Guide NAFO Area - 2010. (A pictorial Identification Guide for some species of Sponge found on the Grand Banks of Newfoundland and Flemish Cap produced in full-colour on waterproof/tearproof stock)	30.00	35.00
Coral Identification Guide NAFO Area - 2009. (A pictorial Identification Guide for some species of Coral found on the Grand Banks of Newfoundland and Flemish Cap produced in full-colour on waterproof/tearproof stock)	25.00	30.00
Identification Guide of Wolffish, Hake and Rockling in the Northwest Atlantic - 2007. (1-page Identification Guide produced in full-colour on laminated stock)	10.00	15.00
Journal of Northwest Atlantic Fishery Science - *Available FREE online at https://journal.nafo.int*		
This publication provides an international forum for the primary publication of original research papers on fisheries science in the Northwest Atlantic, with emphasis on environmental, biological, ecological and fishery aspects of the living marine resources and ecosystems.		
Please note: Scientific publications during ICNAF times (1949–1979) are available at the Secretariat in print format and also available online at www.nafo.int		
Vol. 57, 2026 (Special Issue)	Online only	
Vol. 56, 2025 (Regular Issue)	Online only	
Vol. 54, 2023 (Regular Issue)	Online only	
Vol. 53, 2022 (Regular Issue)	Online only	
Vol. 52, 2021 (Regular Issue)	Online only	
Vol. 51, 2020 (Regular Issue)	40.00	45.00
Vol. 50, 2019 (Regular Issue)	40.00	45.00
Vol. 49, 2017 (Regular Issue)	40.00	45.00
Vol. 48, 2016 (Regular Issue)	40.00	45.00

Vol. 47, 2015 (Regular Issue)	40.00	45.00
Vol. 46, 2014 (Regular Issue)	40.00	45.00
Vol. 45, 2013 (Regular Issue)	40.00	45.00
Vol. 44, 2012 (Regular Issue)	40.00	45.00
Vol. 43, 2010-2011 (Regular Issue)	40.00	45.00
Vol. 42, 2009-2010 (The Role of Marine Mammals in the Ecosystem in the 21st Century)	40.00	45.00
Vol. 41, 2008-2009 (Reproductive and Recruitment Processes of Exploited Marine Fish Stocks)	40.00	45.00
Vol. 40, 2008 (Regular issue)	40.00	45.00
Vol. 39, 2007-2008 (Environmental and Ecosystem Histories in the Northwest Atlantic – What Influences Living Marine Resources?)	40.00	45.00
Vol. 38, 2007 (Regular issue)	40.00	45.00
Vol. 37, 2005-2007 (Flemish Cap Symposium)	40.00	45.00
Vol. 36, 2005-2006 (Regular issue)	36.00	41.00
Vol. 35, 2005 (Symposium on Elasmobranch Fisheries: Managing for Sustainable Use and Biodiversity Conservation)	46.00	51.00
Vol. 34, 2004 (Mini-symposium on Hydrographic Variability in NAFO Waters for the Decade 1991–2000 in Relation to Past Decades)	31.00	36.00
Vol. 33, 2003 (Reproductive Potential of Fish Populations of the North Atlantic)	31.00	36.00
Vol. 32, 2003 (Regular issue)	31.00	36.00
Vol. 31, 2003 (Joint NAFO/ICES/CSIRO Symposium entitled "Deep-Sea Fisheries")	41.00	46.00
Vol. 30, 2002 (Regular issue)	31.00	36.00
Vol. 29, 2001 (Regular issue)	31.00	36.00
Vol. 28, 2000 (Special Issue on A Review of the Cod Fisheries at Greenland, 1910–1995)	31.00	36.00
Vol. 27, 2000 (NAFO/ICES/PICES Symposium on Pandalid Shrimp Fisheries – Science and Management at the Millennium)	41.00	46.00
Vol. 26, 2000 (Regular issue)	31.00	36.00
Vol. 25, 1999 (Variations in Maturation, Growth, Condition and Spawning Stock Biomass Production in Groundfish)	Out of Print	
Vol. 24, 1998 (Regular issue)	26.00	31.00
Vol. 23, 1998 (What Future for Capture Fisheries)	36.00	41.00
Vol. 22, 1997 (NAFO/ICES Symposium on The Role of Marine Mammals in the Ecosystem)	31.00	36.00
Vol. 21, 1997 (Regular issue)	26.00	31.00
Vol. 20, 1996 (Special Issue on North Atlantic Fishery Management Systems: A Comparison of Management Methods and Resource Trends)	26.00	31.00
Vol. 19, 1996 (Gear Selectivity/Technical Interactions in Mixed Species Fisheries Symposium)	26.00	31.00
Vol. 18, 1996 (Regular issue)	23.00	28.00
Vol. 17, 1994 (Special Issue on Report of the Canada–USSR Capelin Symposium)	21.00	26.00
Vol. 16, 1994 (Regular issue)	21.00	26.00
Vol. 15, 1993 (Special Issue on Decapod Crustacean Larvae from Ungava Bay)	21.00	26.00
Vol. 14, 1992 (Special Session on Changes in Biomass, Production and Species Composition)	21.00	26.00
Vol. 13, 1992 (Regular issue)	16.00	21.00
Vol. 12, 1992 (Regular issue)	16.00	21.00
Vol. 11, 1991 (Regular issue)	16.00	21.00
Vol. 10, 1990 (Special issue on The Delimitation of Fishing Areas in the Northwest Atlantic)	16.00	21.00
Vol. 9, No. 2, 1989 (Regular issue)	16.00	21.00
Vol. 9, No. 1, 1989 (Regular issue)	16.00	21.00
Vol. 8, 1988 (Regular issue)	16.00	21.00
Vol. 7, No. 2, 1987 (Regular issue)	16.00	21.00
Vol. 7, No. 1, 1986 (Regular issue)	16.00	21.00

Vol. 6, No. 2, 1985 (Regular issue)	16.00	21.00
Vol. 6, No. 1, 1985 (Regular issue)	16.00	21.00
Vol. 5, No. 2, 1984 (Regular issue)	16.00	21.00
Vol. 5, No. 1, 1984 (Regular issue)	16.00	21.00
Vol. 4, 1983 (Guide to the Early Stages of Marine Fishes in the Western North Atlantic Ocean, Cape Hatteras to the Southern Scotian Shelf)	26.00	31.00
Vol. 3, No. 2, 1982 (Regular issue)	14.00	19.00
Vol. 3, No. 1, 1982 (Regular issue)	14.00	19.00
Vol. 2, 1981 (Regular issue)	14.00	19.00
Vol. 1, 1980 (Regular issue)	14.00	19.00

NAFO Scientific Council Reports - *Available FREE online at www.nafo.int*

This publication contains reports of Scientific Council Meetings held through each year since NAFO replaced ICNAF. (The comparable publication during ICNAF was entitled the *Redbook*).

2025 (issued May 2026)	Online only	
2024 (issued May 2025)	Online only	
2023 (issued May 2024)	Online only	
2022 (issued Mar 2023)	Online only	
2021 (issued May 2022)	Online only	
2020 (issued May 2021)	Online only	
2019 (issued May 2020)	Online only	
2018 (issued Apr 2019)	Online only	
2017 (issued May 2018)	Online only	
2016 (issued Apr 2017)	Online only	
2015 (issued Apr 2016)	Online only	
2014 (issued Jan 2015)	Online only	
2013 (issued Jan 2014)	Online only	
2012 (issued Jan 2013)	36.00	41.00
2011 (issued May 2012)	36.00	41.00
2010 (issued April 2011)	36.00	41.00
2009 (issued May 2010)	36.00	41.00
2008 (issued May 2009)	36.00	41.00
2007 (issued May 2008)	36.00	41.00
2006 (issued May 2007)	36.00	41.00
2005 (issued May 2006)	36.00	41.00
2004 (issued January 2005)	36.00	41.00
2002/2003 Supplement (issued January 2004)	21.00	26.00
2002/2003 (issued August 2003)	31.00	36.00
2002 (issued January 2003)	31.00	36.00
2001 (issued January 2002)	31.00	36.00
2000 (issued January 2001)	29.00	34.00
1999 (issued January 2000)	29.00	34.00
1998 (issued January 1999)	26.00	31.00
1997 (issued January 1998)	23.00	28.00
1996 (issued January 1997)	23.00	28.00
1995 (issued January 1996)	23.00	28.00
1994 (issued January 1995)	21.00	26.00
1993 (issued January 1994)	21.00	26.00
1992 (issued December 1992)	18.00	23.00

1991 (issued December 1991)	16.00	21.00
1990 (issued December 1990)	14.00	19.00
1989 (issued December 1989)	14.00	19.00
1988 (issued December 1988)	12.00	17.00
1987 (issued December 1987)	12.00	17.00
1986 (issued December 1986)	12.00	17.00
1985 (issued December 1985)	12.00	17.00
1984 (issued December 1984)	12.00	17.00
1983 (issued December 1983)	12.00	17.00
1982 (issued December 1982)	12.00	17.00
1981 (issued December 1981)	12.00	17.00
1979–80 (issued December 1980)	12.00	17.00

NAFO Scientific Council Studies: This publication includes papers of topical interest and importance to the current and future activities of Scientific Council.

No. 48, 2017 (Annual Temperature Curves in Twelve Regions of the Gulf of Maine 1985–2013)	Online only	
No. 47, 2015 (Coral, Sponge, and Other Vulnerable Marine Ecosystem Indicator Identification Guide, NAFO Area)	Online only	
No. 46, 2014 (Protocols of the EU bottom trawl survey of Flemish Cap)	Online only	
No. 45, 2013 (NAFO Secretariat. NAFO Research Vessel Stock-by-Stock Surveys Summary 2000–2010)	Online only	
No. 44, 2012 (Report of the Workshop on Implementation of Stock Reproductive Potential into Assessment and Management Advice for Harvested Marine Species)	Online only	
No. 43, 2010 (Sponge Identification Guide - NAFO Area)	Online only	
No. 42, 2009 (Coral Identification Guide - NAFO Area)	Online only	
No. 41, 2008 (Report of the Greenland Halibut (*Reinhardtius hippoglossoides*) Age Determination Workshop)	Online only	
No. 40, 2007 (Identification of Wolffish, Hake and Rockling in the Northwest Atlantic)	Online only	
No. 39, 2005 (Workshop on Mapping and Geostatistical Methods for Fisheries Stock Assessment)	31.00	36.00
No. 38, 2005 (Yellowtail Flounder Ageing Manual)	36.00	41.00
No. 37, 2003 (Working Group on Reproductive Potential)	41.00	46.00
No. 36, 2003 (Workshop on Assessment Methods)	41.00	46.00
No. 35, 2002 (Workshop: The Canada-United States Yellowtail Flounder Age Reading)	31.00	36.00
No. 34, 2001 (Regular issue)	31.00	36.00
No. 33, 2000 (Regular issue)	31.00	36.00
No. 32, 1999 (Regular issue)	31.00	36.00
No. 31, 1998 (Regular issue)	31.00	36.00
No. 30, 1997 (Miscellaneous Selected Papers)	26.00	31.00
No. 29, 1997 (Selected Studies Related to Assessment of Cod in NAFO Divisions 2J+3KL)	26.00	31.00
No. 28, 1996 (Assessment of Groundfish Stocks Based on Bottom Trawl Survey Results	26.00	31.00
No. 27, 1996 (Miscellaneous Selected Papers)	26.00	31.00
No. 26, 1996 (Selected Papers on Harp and Hooded Seals)	26.00	31.00
No. 25, 1996 (Flemish Cap Selected Environmental and Other Papers)	26.00	31.00
No. 24, 1996 (Symposium on Impact of Anomalous Oceanographic Conditions at the Beginning of the 1990s in the Northwest Atlantic on the Distribution and Behaviour of Marine Life)	26.00	31.00
No. 23, 1995 (Miscellaneous Selected Papers)	26.00	31.00
No. 22, 1995 (Miscellaneous Selected Papers)	26.00	31.00
No. 21, 1994 (Collection of Papers Related to Northern Cod and Seals in NAFO Divisions 2J and 3KL)	26.00	31.00
No. 20, 1994 (Miscellaneous Selected Papers)	26.00	31.00
No. 19, 1993 (Miscellaneous Selected Papers)	21.00	26.00

No. 18, 1993 (Symposium on Changes in Abundance and Biology of Cod Stocks and Their Possible Causes)	21.00	26.00
No. 17, 1993 (Workbook: Introduction to Sequential Population Analysis)	18.00	23.00
No. 16, 1991 (Special Session on Management Under Uncertainties, 5–7 September 1990)	21.00	26.00
No. 15, 1991 (Miscellaneous Selected Papers)	18.00	23.00
No. 14, 1990 (Miscellaneous Selected Papers)	18.00	23.00
No. 13, 1989 (Miscellaneous Selected Papers)	18.00	23.00
No. 12, 1988 (Miscellaneous Selected Papers)	18.00	23.00
No. 11, 1987 (Miscellaneous Selected Papers)	18.00	23.00
No. 10, 1986 (Miscellaneous Selected Papers)	18.00	23.00
No. 9, 1985 (Special Session on Squids, September 1984)	21.00	26.00
No. 8, 1985 (Miscellaneous Selected Papers)	16.00	21.00
No. 7, 1984 (Miscellaneous Selected Papers)	14.00	19.00
No. 6, 1983 (Miscellaneous Selected Papers)	14.00	19.00
No. 5, 1982 (Symposium on Environmental Conditions in the Northwest Atlantic During 1970–79, September 1981)	14.00	19.00
No. 4, 1982 (Special Session on Remote Sensing September 1981)	14.00	19.00
No. 3, 1982 (Miscellaneous Selected Papers)	12.00	17.00
No. 2, 1982 (Manual on Groundfish Surveys in the Northwest Atlantic)	11.00	16.00
No. 1, 1981 (Miscellaneous Selected Papers)	12.00	17.00

Statistical Bulletin - *Available FREE online at https://www.nafo.int/Library/Science-Council/Statistical-Bulletin*

Complete statistical data have been published in the Statistical Bulletin since 1951. The printed version of the statistics were discontinued after Vol. 49 - 1999. The electronic **STATLANT 21B** database is updated regularly as new information becomes available.

Information for Preparing Manuscripts

The *Journal of Northwest Atlantic Fishery Science* is a longstanding peer-reviewed journal focusing on all aspects of marine fisheries science and fisheries management. Journal topics span marine biology, ecology, stock assessment, fisheries technology, oceanography, policy, and socioeconomics. The journal primarily focuses on the Northwest Atlantic Ocean but welcomes any contribution of general applicability to fisheries science.

- **Original research articles:** contain the details and results of original pieces of research. Original research articles should not exceed 20 pages (double-spaced), not including tables and figures. These contributions must follow a prescribed format, as described below.

- **Review articles:** typically contain articles that summarize, analyze, interpret and synthesize existing research on a particular topic. These contributions can have a more free-ranging structure, without necessarily prescribed section headings, etc. Review articles should not exceed 30 pages (double-spaced), not including tables and figures.

All manuscripts should be submitted in English as a Word document (**Times New Roman 10 point font**) that is double-spaced with page and line numbering throughout. Referees are not asked to conduct English language editing so please have your manuscript reviewed for such, if necessary, prior to submittal.

Authors are required to provide the Journal Editors with the names and e-mail addresses of at least two appropriate reviewers for their manuscript. Authors should not have a conflict of interest with the reviewers they recommend.

Research Article Organization

All manuscripts should begin with a title, abstract, and keywords as described below. Authors should be guided by the organization of papers that have been previously published in JNAFS.

Title: The manuscript should begin with the title, followed by the name(s), address(es) and e-mails of the author(s) including professional affiliation(s), and any related footnotes. The name and e-mail address of the corresponding author should be provided.

Abstract: The abstract should provide an informative, concise summary of the manuscript but should not exceed 300 words in length.

Keywords: The Keywords section should include four to five keywords, listed alphabetically, that are useful search terms for the article.

Original research articles should be sequentially organized into the following sections: Introduction, Materials and Methods, Results, Discussion, and Acknowledgments. Note that review papers are not necessarily confined to this rigid structure.

1. **Introduction:** The Introduction section should include the purpose and rationale of the study and any background information necessary for the reader to understand the study topic and or context. Text citations should list references by date rather than alphabetically.

2. **Materials and Methods:** The Materials and Methods section should describe in sufficient detail the methods used, to enable other scientists to evaluate and replicate the work.

3. **Results:** The Results section should answer the questions evolving from the purpose of the study in a comprehensive manner in an orderly and coherent sequence, with supporting tables and figures.

4. **Discussion:** The Discussion section should explain the main contributions from the study, with appropriate interpretation of the results focusing on the problem or hypothesis.

5. **Acknowledgements**: The Acknowledgements section should be limited to the names of individuals who provided significant scientific and technical support, including reviews, during the preparation of the manuscript, and the names of agencies which provided financial support.

6. **References:** The References cited in the text should be listed using APA style, alphabetically by the first author, then by date. The Digital Object Identifier (DOI) should be included if available. The following URL can be used to check this https://www.crossref.org/guestquery/. References should be mainly restricted to primary English journal publications but may include other types of published literature. Website references should include the URL and access date. Unpublished documents and data, papers in preparation and papers awaiting acceptance to other journals may be cited with full contact addresses as unpublished or personal communications.

Examples of Reference formats:

Journal:

Pares, P., and Britain, B. 1965. Predator–prey behaviour of herring (*Clupea harengus albertus*). *International Journal of Applied Biology*, 24: 132–135.

Book:

Havfrue, D. L. 1990. Ecological implications of genetic mutation. *In* F. Ray, and O. Lith (Eds.), *Studies in Parthenogenesis*, 2nd ed., pp. 282–289. Thalassa Press, London.

Meeting document:

Ávila de Melo, A. M., D. Power and R. Alpoim. MS 2005. An assessment of the status of the redfish in NAFO Division 3LN, *NAFO SCR Doc*., No. 52, Serial No. 5138, 19 p.

Supplementary Materials

Articles may include supplementary materials and are displayed as a separate document next to the main article, in a PDF format. They are published as is and are not formatted by the journal.

Units of Measurement and Time

Articles may include supplementary materials and are displayed as a separate document next to the main article, in a PDF format. They are published as is and are not formatted by the journal.

Tables and Figures

All tables and figures must be cited in the text and numbered consecutively within the text. Each table and figure should have a concise descriptive caption. Each table and figure should be submitted separately or as zipped files. See table for guidance.

We prefer .wmf, .emf, .ps, .eps files for vector figures. Raster images such as photos, pictures, maps can be in .jpeg, .png, .tiff formats and should be 300 ppi (high resolution).

Instructions for creating plots in R for JNAFS.

Format	Driver	Notes
JPEG	jpg	Joint Photographic Experts Group; can be used anywhere; doesn't resize, raster image
PNG	png	Portable Network Graphic; used for screens only; doesn't resize
TIFF	tif	Tagged Image File Format; can be used for print; raster image; doesn’t resize
SVG	svg	Scalable Vector Graphic; easily resizable; can be used for vectors; web only
AI	.ai	Adobe Illustrator; easily resizable; can be used for vectors
EPS	.eps	Encapsulated Postscript; easily resizable; can be used for vectors
EMF	.emf	Enhanced Windows Metafile; best choice with Word; easily resizable; can be used for vectors
WMF	win.metafile	Windows Metafile Format only; best choice with Word; easily resizable; can be used for vectors
PDF	pdf	Portable Document File; best choice with pdflatex; easily resizable; can be used for vectors
PS	postscript	Best choice with latex and Open Office; easily resizable; can be used for vectors

Green highlight – raster format; blue highlight – vector format

Submissions

Manuscripts should be submitted by logging into Scholastica, JNAFS online submission platform.

https://jnafs.scholasticahq.com/for-authors

https://app.scholasticahq.com/login

All authors need to register/sign-up first before submitting manuscripts using the link above.