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Food for Thought

Operationalizing integrated ecosystem assessments within a multidisciplinary team: lessons learned from a worked example

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Between 2014 and 2016, an interdisciplinary team of researchers including physical oceanographers, biologists, economists and anthropologists developed a working example of an Integrated Ecosystem Assessment (IEA) for three ecologically distinct regions of the Northwest Atlantic; Georges Bank, the Gulf of Maine and the Grand Banks, as part of the International Council for the Exploration of the Sea (ICES) Working Group on the Northwest Atlantic Regional Sea (WGNARS). In this paper, we review the transdisciplinary and collaborative process by which the IEA was developed, with a particular focus on the decision points arising from the IEA construct itself. The aim is to identify key issues faced in developing any IEA, practical decisions made to address these issues within the working group and lessons learned from the process.

Keywords: IEA, Northwest Atlantic, transdisciplinary research.

Introduction

Integrated Ecosystem Assessments (IEA) are a broad category of frameworks that generally look to support ecosystem-based management, with the particular definition stemming from the regional management regime in which it is undertaken (see, for example, ICES, 2010). Since its inception in 2009, the ICES Working Group on the Northwest Atlantic Regional Sea (WGNARS) has been focused on building capacity to support IEAs for the Northeastern US and Atlantic Canada. The key objective of this effort is to draw on as broad a base of expertise as possible, ranging from managers to scientists, and across disciplines in a manner that describes the ecosystem from large-scale abiotic physical processes through the human benefits derived. Somewhat surprisingly because "integrated" is a component of the acronym, there are very few examples of IEA working groups that reflect such a broad range of disciplines, particularly within the ICES regional seas programme (see Harvey *et al.*, 2014 for one of the few examples globally). Given this, the current paper describes the process used in developing an IEA for the Northwest Atlantic, with the goal of identifying the decision points and lessons learned that would be of use to other groups embarking on similar initiatives. In particular, we focus on the decisions critical to moving the group through four distinct phases of work (Figure 1). In the first phase, the group began as an expert group sharing information across disciplines and developing an inventory of potential indicators for system assessment. The second phase involved identifying objectives for the IEA by drawing from existing regulations and guidance documents. In the third phase, the objectives and indicators served as essential guides to developing collaborative and holistic interdisciplinary models of the system. In the fourth and the final phase, the knowledge gleaned from the IEA development process is beginning to be filtered into the US management process. It should be noted that although Figure 1 is unidirectional in its flow, each phase consists of feedback loops. For example, as information was communicated by the group, it led to the identification or development of additional indicators to fill previous gaps and enhance our ability to track progress towards objectives. The majority of this paper focuses on phases 2 and 3, and progresses as follows: the motivation and framework adopted for the IEA is explained in the Background section; the decision points encountered during the process are discussed in the Process section; and the Conclusion section details gaps in the process that are likely to affect the robustness of IEA results, identifies key lessons learned by the group, and outlines future work aimed at addressing some of these gaps.

Background

WGNARS is an expert working group under the ICES Science Steering Group on Integrated Ecosystem Assessments (SSGIEA). The Regional Sea Programme was established to overcome perceived challenges to implementing an ecosystem approach to management (EAM). The SSGIEA promotes IEAs as a framework to assess ecosystem management objectives and engage relevant stakeholders and decision makers (Walther and Möllmann, 2014).

Between 2009 and 2012, WGNARS meetings functioned like a symposium, with a multidisciplinary group of scientists presenting research and data products that could be used to support an IEA for the Northwest Atlantic. These initial meetings provided the opportunity for participants to share knowledge, relevant research and capabilities, and importantly, to begin to build the interpersonal relationships that would support later steps in the process. However, these initial meetings were limited in their ability to move the IEA process forward in that they were not guided by a common set of regional IEA objectives. In 2013, the format changed to include fewer presentations, more focused discussions, and targeted collaboration, with the explicit goal of delivering a working example of an IEA by the end of 2016.

Management of ocean and fisheries resources in the Northwest Atlantic resides primarily in the US National Oceanic and Atmospheric Administration (NOAA), Fisheries and Oceans Canada, and the North Atlantic Fisheries Organization, with ICES providing no direct management advice. This means the work undertaken by WGNARS does not directly feed into the management process. Instead, the group has focused on building capacity, with substantial flexibility in defining the group's terms of reference. Nevertheless, the core membership of WGNARS is drawn from NOAA Fisheries and Fisheries and Oceans Canada Science and Ecosystem Management staff, with a large contingent of collaborators from other federal departments, academia, NGOs and fisheries management body staff. The group's work has begun to indirectly support managers.

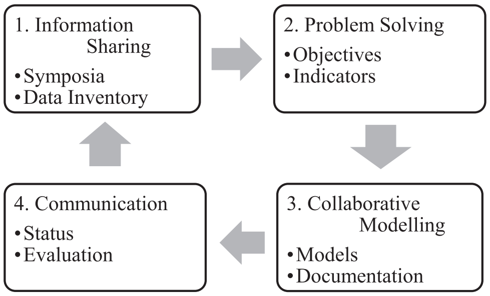

Figure 1. Diagram of the process by which WGNARS transitioned from an expert group sharing information to a collaborative modelling working group generating and communicating shared products.

Since its inception, WGNARS has been guided by the work of Levin *et al.* (2008, 2009). The Levin *et al.* approach is an iterative process that includes defining goals and targets, developing indicators, assessing the system, analyzing uncertainty and risk, and management strategy evaluation (Figure 2). It is important to note that numerous other working definitions for IEA exist which could have been adopted (ICES, 2010). However, the Levin *et al.* approach best supported the needs of both Canadian and US participants. The subsequent sections highlight how WGNARS addressed each portion of the IEA process. Although the discussion of the process is structured around the Levin *et al.* methodology, we also detail the collaborative process when appropriate.

Process

Scoping and objective identification

Scoping identifies regional societal objectives, which are then used to formulate key questions to guide the IEA and to determine the associated scope of research and assessment (spatial, temporal, social and ecological). Scoping is a critical component of the management process and should be as inclusive as possible. The WGNARS membership consists primarily of scientists, and lacks direct input from managers in either Canada or the US. However, the group felt very strongly that objectives should not be identified by scientists but rather should be drawn from existing legislative mandates and management documents as well as from stakeholder input (managers, fishermen, coastal community members, the public and others). While desirable, a full public scoping process was not feasible due to timing and funding constraints, as well as lack of a direct management mandate, so a review of existing regulations and policies spanning the region was considered a proxy. Ultimately, key documents that informed this process included the US Magnuson-Stevens Fisheries Conservation and Management Act, and its amendments, as well as the Canada Fisheries Act. Although there was substantial concern regarding the validity of objectives developed in this manner, group members' previous interactions with managers indicated that worked examples can greatly facilitate the development of management objectives by catalyzing discussion. The group thus adopted the objectives with the understanding that these were strawmen that could be replaced or revised with input from a public scoping process and the belief that the example would be of substantial utility if presented in this light. The group also noted additional objectives, such as cultural practices and attachments, which a broad swath of literature identifies as a benefit derived from, and moderator of, fishing activities (Gatewood and McCay, 1990; Pollnac and Poggie, 2008; Smith and Clay, 2010), including sense of place (Power and Paolisso, 2007; Hausmann *et al.*, 2016). Although not presented in the formal system objectives, these additional objectives were incorporated in the conceptual models described below, to ensure representation. The group thus capitalized on its member expertise while preserving the external validity of the formal objectives, the latter having been derived solely from extant management regulations. Ultimately, the New England Fishery Management Council's adoption of the objectives, with some expansion and revision, within their risk policy (New England Fishery Management Council, 2016) indicates they resonate broadly with both managers and stakeholders. The objectives themselves represented the first tangible results from phase 2 of the WGNARS work (Figure 1). The strategic objectives are identified in Table 1, while a more detailed list is presented in the online Supplementary Material Section S1.

Focusing on legislated objectives led to a number of important practical outcomes. First, drawing objectives from an external source allowed the group to overcome barriers associated with the communication and defence of each individual discipline's values and priorities, which fostered a transdisciplinary approach to the work. (Here we make the distinction between multidisciplinary work, in which each discipline informs the others in their work but rigid disciplinary boundaries are enforced, and transdisciplinary work, in which an integrated and contextualized worldview is presented. See Paterson *et al.* (2010) for a more thorough discussion of transdisciplinary research with respect to fisheries management.) The move away from the work of developing objectives towards the development of indicators and targets for existing objectives shifted participation from negotiation to considering how our collective disciplines could contribute to assessing the status of the regional ecosystem, a core component of transdisciplinary research. However, the identification of key objectives also illuminated the theoretical complexities and practical tradeoffs associated with the full breadth of tradeoffs between fishery, habitat, social and economic objectives in a transdisciplinary sense. For example, decreased landings utilized for seafood vs. industrial or bait uses may not be an indicator of declining economic value, as the market is allocating those resources to their most valuable use. However, other social science disciplines see the use of potential food for non-food products as an ethical issue associated with social and environmental justice concerns. Second, legislated objectives tend to be vague, with few specifics to facilitate development of fully operational objectives and associated indicators. The WGNARS objectives were developed taking into account the specific, measurable, achievable, relevant, and time-bound (SMART) criteria (Doran, 1981), a concept developed in business management to help construct effective operational objectives. (Doran's criteria defined assignable rather than achievable as a criterion, but achievable is also in wide use.) Only fish stock status determination has the specificity in federal regulations to allow all five SMART criteria to be met. Conversely, neither the habitat nor social objectives met the specific, measurable and time-bound criteria, due in no small part to the manner in which they are caveated in the US Magnuson-Stevens Fishery Conservation and Management Act (MSA) and the Canada Fisheries Act. For example, Title III Sec. 301 of the MSA states "Conservation and management measures shall, where practicable, consider efficiency in the utilization of fishery resources; except that no such measure shall have economic allocation as its sole purpose" (Magnuson-Stevens Fishery Conservation and Management Reauthorization Act, 2007). Thus, the MSA explicitly states that economic efficiency must be traded off against other objectives, but the levels of efficiency which must be attained are not identified. This proved problematic for setting thresholds for indicators, which is discussed below in more detail.

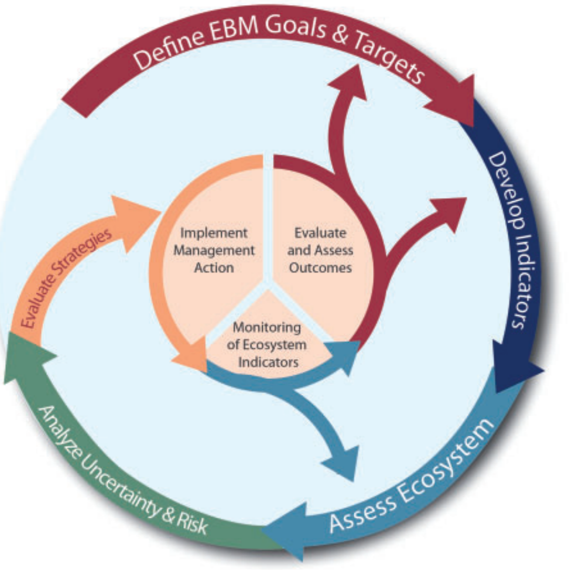

Figure 2. Conceptual diagram of the Integrated Ecosystem Assessment reproduced from Levin, P. S., Fogarty, M. J., Murawski, S. A., and Fluharty, D. 2009. Integrated ecosystem assessments: Developing the scientific basis for ecosystem-based management of the ocean. PLoS Biology, 7(1): 23–8, with permission from NOAA Fisheries.

Consistent with research on the Northwest Atlantic in both Canada and the US, the group adopted ecoregions as the appropriate spatial extent for which the IEA should be conducted (Pepin *et al.*, 2010; Pérez-Rodriguez *et al.*, 2010; Fogarty *et al.*, 2011; Pepin *et al.*, 2012; Lucey and Fogarty, 2013). In order to leverage available data and existing work, focus scarce resources and contrast human uses, management structures, and national jurisdictions, WGNARS selected the Georges Bank/Gulf of Maine ecoregions in the US and the Grand Banks ecoregion in Canada (Figure 3).

Given WGNARS membership expertise, the spatial focus, and fishery managers as primary clients, the IEA centres on fisheries issues. In this manner, the work is best viewed as supporting ecosystem-based fishery management (EBFM) as opposed to the broader ecosystem-based management (EBM) paradigm. (Ecosystem-based fisheries management considers all the interactions within the fisheries sector, but none between fisheries and other sectors of the economy.) Although somewhat restricting the overall applicability of the IEA, the group felt that the challenges

Table 1. Canadian and US strategic objectives.

Country	Strategic objective
US	Maintain fishing mortality within target reference points
US, Canada	Protect and/or facilitate recovery of at-risk or depleted species
US	Individual species mortality below threshold
US	Maintain total harvested species biomass above a dynamic biomass threshold
US	Maintain fish population size structure within acceptable limits
US	Maintain trophic structure within acceptable limits
US	Maintain functional group/guild structure within acceptable limits
US	Maintain habitat productivity
US	Maintain habitat diversity
US, Canada	Maintain habitat structure and function
US	Minimize risk of permanent (>20 years) impacts
US	Optimize food provision
US	Optimize economic profitability
US	Optimize employment
US	Optimize recreation
US	Optimize stability
Canada	Maintain healthy biomass and productivity of harvested and other species
Canada	Support conservation of biodiversity at local, regional, and national scales
Canada	Optimize ocean sector revenues
Canada	Optimize ocean sector employment

to operationalizing EBFM were substantial and would need to be overcome prior to leaping into the full EBM paradigm. However, the group also felt a key benefit of the IEA framework, and EBM more broadly, is assessing trade-offs that are otherwise ignored. In both Canadian and US waters, use conflicts and the allocation of benefits (e.g. employment vs. economic welfare) between fisheries and the energy sector are highly visible issues. WGNARS thus settled on incorporating both fisheries and energy into the IEA as a small step towards EBM, with the understanding that additional expertise and participation was necessary to successfully expand the scope of work.

Although collaboration was sought, WGNARS was unable to attract the participation of individuals with expertise in US energy policy. This shortfall likely resulted from the fact that, although there is substantial interest in wind energy within the eastern US, it is concentrated in the Mid-Atlantic ecoregion. Given that the Mid-Atlantic was not slated for immediate assessment, WGNARS could not fully consider or communicate the immediate benefits such collaboration would provide partners outside of fisheries. Nevertheless, the group ultimately drew upon expertise from a sizable contingent of participants across the 3-year period, with over 50 individuals engaging in either the working meetings themselves or contributing directly to the work presented. The dynamic nature of the group, with an average of 25 individuals participating in each of the three annual meetings, helped address any potential bias due to group membership and allowed experts to be drawn in as needed.

Indicator development

The Northwest Atlantic is generally considered a data-rich region of the world's oceans, with long-time series available to track the majority of the objectives. These indicators are identified in the online Supplementary Material Section S1. The working group had developed extensive inventories of potential indicators during phase 1 of the work (Figure 1), and the majority of indicators were drawn directly from this inventory.

A number of technical and methodological issues proved vexing in regards to the IEA. As previously mentioned, the lack of operational objectives precluded the identification of thresholds from which to assess the achievement of objectives. This issue was compounded by the lack of manager-derived weightings across objectives (e.g. how many jobs is a hectare of coral worth?). (Of note is that a lack of explicit weights on indicators still represents an implicit subjective weight for these indicators, with each indicator given equal importance in management advice.) Only fishery stock biomass levels were defined in supporting US legislation with any amount of specificity (that which provides maximum sustainable yield, less any ecological and economic concerns).

Given this reality, WGNARS members approached the development of indicator thresholds in as neutral a manner possible. The group worked under the assumption that historical fishery performance provides some information on the latent objectives of management, and adopted a mean-variance measure of performance for the time series indicators. The specific thresholds warranting closer investigation were observations greater or less than one standard deviation from the mean.

The vast majority of IEA work relies on quantitative approaches to time-series data. However, even in what is viewed as a data rich region of the globe, there is a lack of time-series data that would allow tracking of certain ecosystem components with objectives defined in the relevant regulations. This is particularly true for objectives focused on habitat and societal values, and generally results from the complexity and cost of developing new long-term data streams at the scale needed to continually and consistently assess an ecosystem. One critical issue that WGNARS will be exploring over the coming years is how to better integrate qualitative data into the IEA process in a meaningful manner.

The existing list of time-series indicators were scored against the ICES Working Group on Ecosystem Effects of Fishing Activities (WGECO)/Working Group on Biodiversity Science (WGBIODIV) indicator criteria (see example scoring in the online Supplementary Material Section S2), originally developed in support of the European Union's Marine Strategy Framework Directive (ICES, 2013). WGNARS found that the WGECO/WGBIODIV indicator criteria were not flexible enough to assess all classes of indicators under consideration. For example, the binary classification of state or pressure (Criterion 1) is particularly problematic for indicators of human well-being (e.g. revenue, recreational fishing trips, seafood provision), which are neither (or both). This disconnect propagates throughout a number of the other criteria, including the fact that indicators for human well-being are not fully manageable (Criterion 6) as they are partially determined by forces, such as consumer preferences, outside the control of managers.

Beyond the theoretical disconnect between the indicators developed by WGNARS and the WGECO/WGBIODIV criteria, a number of indicators received low scores due specifically to the process employed in developing them. The lack of clear targets for habitat and human well-being has already been mentioned (Criterion 7). Additionally, only the stock abundance indicators

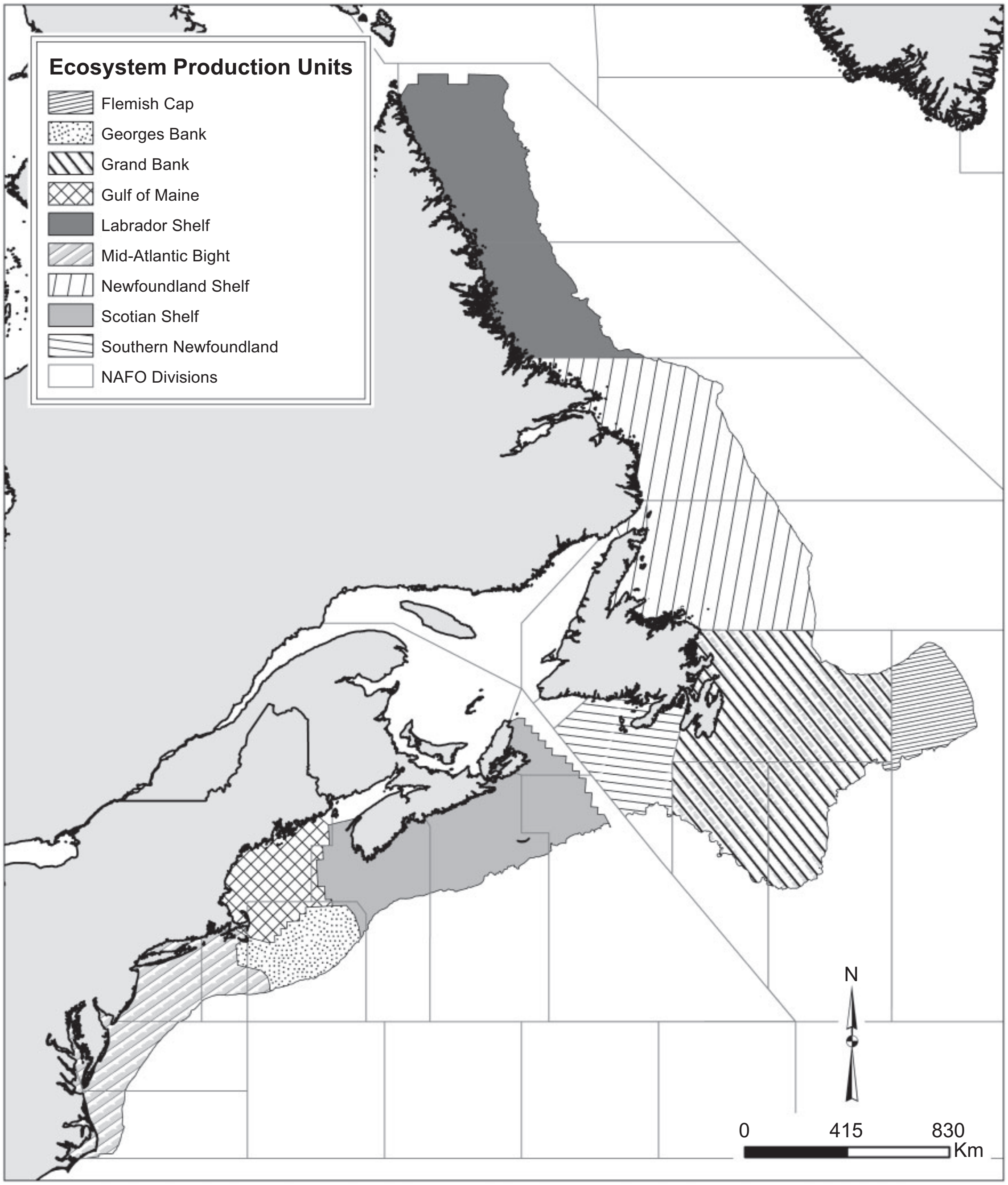

Figure 3. Georges Bank/Gulf of Maine (US) and Grand Banks (Canada) Ecological Production Units, redrawn from NAFO. 2014. Report of the 7th Meeting of the NAFO Scientific Council Working Group on Ecosystem Science and Assessment, November 18–27, 2014, Dartmouth, NS, CA. NAFO SCS Doc. 14/023, with permission from NAFO WGESA.

link directly to a management response in the relevant regulations (Criterion 8).

Overall, although the WGECO/WGBIODIV criteria worked well for indicators for fish stock abundance, their rigidity was problematic when applied to the indicators of human well being, habitat and ecosystem diversity measures. Some of the shortfall lies in the decisions regarding the derivation of objectives from regulations and could be remedied with input from managers. Nevertheless, parts of the conceptual construct were ill matched for the full suite of indicators developed by WGNARS, and the criteria would need expansion and revision to allow the effective assessment of all indicators of interest to managers.

Risk assessment

Risk assessment is a particularly appealing tool for operational IEA, because it directly connects science and management decision-making within a framework that is understood and used across multiple disciplines and industries. Risk assessments themselves deal with measuring the probability and severity of adverse consequences stemming from alternate policies. There are existing frameworks and best practices for environmental risk assessment, including an ISO standard (ISO, 2009a–c). WGNARS reviewed multiple ecological risk assessment methods and examples (US EPA, 1998; Fletcher, 2005; Park *et al.*, 2010; Hobday *et al.*, 2011; Samhouri and Levin, 2012; Cormier *et al.*, 2013), and found that regardless of application, the risk assessment process remains similar. Commonalities across all frameworks include an initial triage or scoping phase to prioritize risks in achieving management objectives, the use of quantitative methods where necessary and possible, and the inclusion of certainty or reliability of information within assessments.

WGNARS conducted a brief, narrow scope assessment of climate risks on cod stocks within the Northwest Atlantic to explore practical issues for IEAs, but did this prior to fully developing a working list of management objectives. Several difficulties were encountered with applying the risk assessment framework, many of which related to lack of clarity in the ground rules for conducting the assessment. This once again highlights the need for thorough scoping of objectives and clearly defining a methodology beforehand. The group had difficulty defining what specific risk was being assessed, and settled on "Risk to resource" which was more general than "Risk to achieving management objectives (e.g. rebuilding, fishing sustainably)". Defining the biological attributes too broadly or in too much detail also led to confusion (e.g. what do we mean by Production? Is it limited to recruitment or growth? Ultimately, it encompassed both of these processes). In working through the anticipated change/attribute pairs, it became clear that the group could only predict three cod responses to climate with any confidence (changes in physiology, phenology and distribution). In trying to permute these changes into the larger set of attributes, the group determined that impacts of changes in community structure or predator-prey interactions would need to be evaluated through modelling exercises to understand even the direction of change; an expert opinion approach is not sufficient for this level of assessment. The risk assessment should thus have been a component of phase 3, instead of at the beginning of phase 2 as actually occurred (Figure 1).

It was noted that getting into too much detail on any aspect of the risk assessment would translate to an impossible task when scaled to the ecosystem level—the skill here is interpreting the science and assessing the risk defensibly, at a broad level that does not overwhelm the process. Once the group agreed to ground rules, identifying impacts, direction and magnitude became easier for each change/attribute pair for cod, and confidence assignments were much easier because rationales had already been developed.

The group concluded that there is a clear need to produce risk assessments where existing methods are adapted for cross-sector risks and levels of organization above the single species. The working group did not have time to identify gaps in knowledge during this exercise, but agreed that this would also be an important component of IEA risk assessment. Overall, the review of the risk assessment frameworks and applications was useful, but further work is necessary to apply some of these frameworks at the IEA scale, given the resource constraints present in our case. In particular, it would be helpful to seek additional advice on reducing complexity in the analysis to achieve consistent and timely results across a large matrix of ecosystem components ranging from individual species to economies and both biological and human communities.

WGNARS members plan to revisit a fuller risk assessment in upcoming years, making use of the identified management objectives and thresholds to assess risk more quantitatively. However, several key points were identified from the initial review. First, existing risk assessment frameworks and best practices should be adopted where possible. However, risk assessment frameworks developed for single species or a limited number of ecosystem attributes may require further adaptation for operational IEAs, including a more structured framework, as recently noted in a comprehensive look at ecosystem-level risk assessment by Holsman *et al.* (2016). Second, terminology should be standardized so that the process is transparent to all participants, and methodology should be clearly defined (and tested) in advance of the analysis. Third, managers and scientists must communicate iteratively and early on in the process to define management needs for decision-making. Challenges include clearly defining objectives for the risk assessment, getting political support to pursue a risk assessment approach, and making the risk assessment approach administratively achievable.

Moving forward, WGNARS suggested that targeted research by scientists can improve aspects of risk assessment and risk communication in a number of ways. For example, cumulative impacts across sectors or uses can be addressed through risk assessment, but many applications to date address linear cumulative effects. More evaluation and investigation of synergistic or antagonistic effects is necessary. Both temporal and spatial scales for risk assessment need to be explicit. Approaches to reducing complexity and standardizing the information databases for analyses should be explored. Finally, qualitative and quantitative modelling is necessary to evaluate risks associated with complex interactions and responses in socio-ecological systems.

In both the US and Canada, the risks of climate impacts on marine ecosystems and resources have been evaluated in more detail since the initial review by WGNARS. A simple hierarchical assessment of climate risk to aggregate fish communities comparing US ecoregions demonstrated that climate risk exposure and community sensitivity varies at the regional scale (Gaichas *et al.*, 2014). Similarly, Stortini *et al.* (2015), using their "Vulnerability to Projected Warming Assessment" tool, concluded that species on the western Scotian Shelf were more vulnerable to increased SST than species on the eastern Scotian Shelf. More extensive analyses of climate risk to marine species (Hare *et al.*, 2016) and fishing communities (Colburn *et al.*, 2016) demonstrate that exposure to climate risk is relatively high in this region, but that species and the human communities that depend on them range from relatively insensitive to highly sensitive to the particular climate risks on the Northeast US shelf. This information is in turn informing fishery managers in the Mid-Atlantic region where recently adopted Ecosystem Approach to Fishery Management policy guidance uses risk assessment as an initial step to prioritize further analysis and action (Gaichas *et al.*, 2016). WGNARS members are currently working with fishery managers to identify and evaluate biological, ecological, social, and economic risks.

Management strategy evaluation

Management strategy evaluation (MSE) employs simulation models to evaluate the performance of alternative sets of management measures for achieving stakeholder-defined objectives (Smith, 1994). Considering uncertainties and identifying tradeoffs between objectives for each management strategy are central

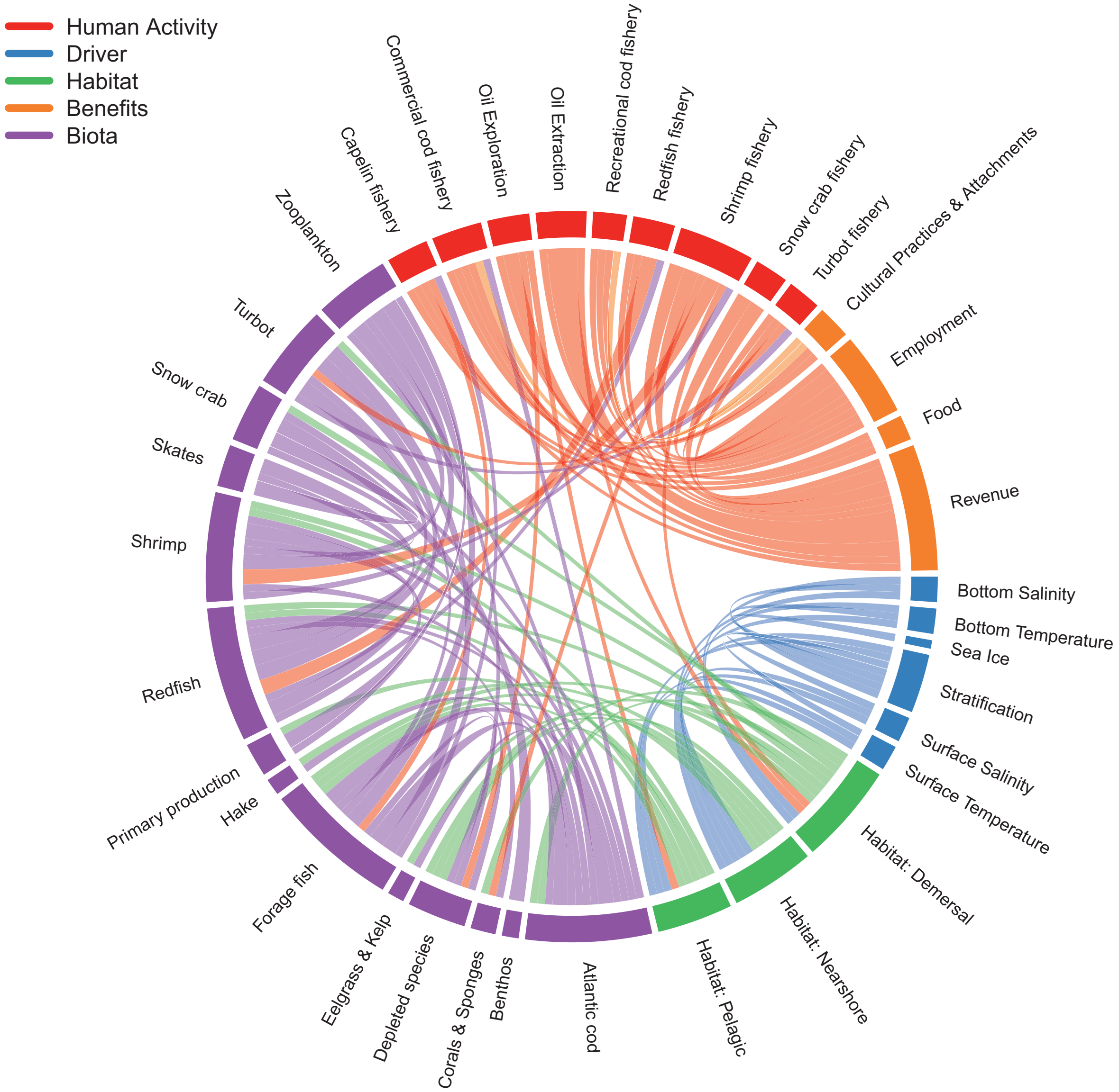

Figure 4. Grand Banks Conceptual Model: System description linking environmental drivers, human activities, ecological interactions, and societal benefits for key ecosystem components, with link width corresponding the absolute magnitude of link.

to the process; this becomes increasingly complex at the ecosystem level, where few MSEs have been conducted to date (Punt *et al.*, 2016). For WGNARS, the goal was to illustrate an ecosystem-level MSE integrating physical and ecological processes as well as human dimensions to provide information on potential trade-offs between objectives. A secondary goal was to evaluate relatively simple methods that could be applied in regions lacking substantial ecosystem and economic modelling resources. This formed the core work associated with phase 3 (Figure 1), and we outline the methods and give example results below; the full MSE description and results are reported elsewhere.

The WGNARS MSE modelling effort began by defining conceptual models of the system. Here we define a conceptual model as a transdisciplinary representation of the system, in which the linkages between system components are delineated in a qualitative manner representing the sign (positive or negative) and magnitude (high, medium and low) of the linkage. This approach allowed the cross-disciplinary integration and standardization of expert knowledge and data. Conceptual models were developed for each ecoregion: Georges Bank, Gulf of Maine, and the Grand Banks. There were two components of each conceptual model: a flow-chart visual representation of the system, and a support table documenting all aspects of the model.

The flow-chart representation of the system details the system components, large-scale drivers, and the linkages between each, including sign, magnitude and direction of the linkages. The California Current IEA conceptual models served as the basis for these flow charts (Levin *et al.*, in press). An initial overview model for each region was developed at the 2015 WGNARS meeting. For the 2016 meeting, Mental Modeler (Gray *et al.* 2013), a versatile collaborative modelling software, was used to develop both the US and Canadian conceptual models. Separate sub-models were developed for the biological, physical and social components of the system and then merged into a full model. A representation

Table 2. Single entry for the support table underlying and describing the conceptual models developed for the US ecoregions.

	FROM		TO					
Submodel	**Focal component**	**Focal element**	**Linked component**	**Linked element**	**Link description**	**Link magnitude**	**Link uncertainty**	**Supporting information**
Ecological Interactions	Georges Bank Forage Fish	Georges Bank Commercial small pelagics	Georges Bank Groundfish	Georges Bank Groundfish	Prey	++	Low, based on food habits data	Summed flows from EMAX (Link et al. 2006) across demersals: omnivores, benthivores, piscivores as total groundfish. EMAX dominant food web flows; >10% as +; >20% as ++ link magnitude

Each link detailed in Figure 4 has a similar entry.

of the Canadian Grand Banks full-system model is provided in Figure 4. Generating each sub-model separately allowed the lens to be shifted between disciplines and sectors (for example, the most important species from a food web perspective is not necessarily the most important to the recreational fishery), and provides a broader representation of the key system components.

The support table provides transparency for the rationale underlying the linkages delineated in the visual representation of the conceptual models. This documentation also allows for reproducibility, a key component of the scientific process. An example entry of the support table is presented in Table 2, slightly modified to fit in the manuscript. Of note is that both the conceptual model and support table are static, in that they represent linkages within a prescribed time horizon. This topic will be addressed in more detail through the discussion of the MSE approaches and results.

Beyond recognizing the static nature of the relationships represented, the support table is key in documenting the nuances that are lost when aggregating species, fleets, or other system components in a conceptual representation. For example, although both the Georges Bank and Gulf of Maine models incorporate a commercial shellfish fishery, the species harvested and technology employed in each is different. In the Gulf of Maine the primary shellfish fishery is a pot fishery targeting lobsters, while the dredge fishery targeting scallops is the dominant component of the Georges Bank shellfish fishery. These nuances have important ramifications for the linkages between the shellfish fishery and other components of the system, and are detailed in the support table to ensure transparency (the full support table is available from the corresponding author upon request).

The completed conceptual models map linkages between system components, ranging from environmental drivers through habitats and food webs to human activities and benefits such as seafood production, employment, profit and others identified above. This framework translates immediately into a qualitative network model of the full system. Qualitative network models (Levins, 1974) are mathematical models in which perturbations are assessed for their qualitative impact on the system of interest (positive, neutral or negative). WGNARS used these qualitative network models as a basis for a simple demonstration MSE. The goal of this approach is to assess the tradeoffs between objectives associated with management strategies across different environmental scenarios, defined here as time periods corresponding to differences in system drivers. During the 2015 WGNARS meeting, two separate time periods (1995–1999 and 2010–2014) were identified for assessing the impact of large-scale drivers on MSE outcomes, and these establish the environmental scenarios. The scenarios for each ecoregion were drawn directly from the quantitative indicators detailed in the conceptual model support tables. This information was then used to scale the magnitude of the effect that individual system components exert on other directly linked components of the system within the qualitative network models. The management strategies themselves corresponded to changing fishing pressure on each fishing fleet across the two environmental scenarios, and assessed relative changes in outcomes related to the previously identified objectives.

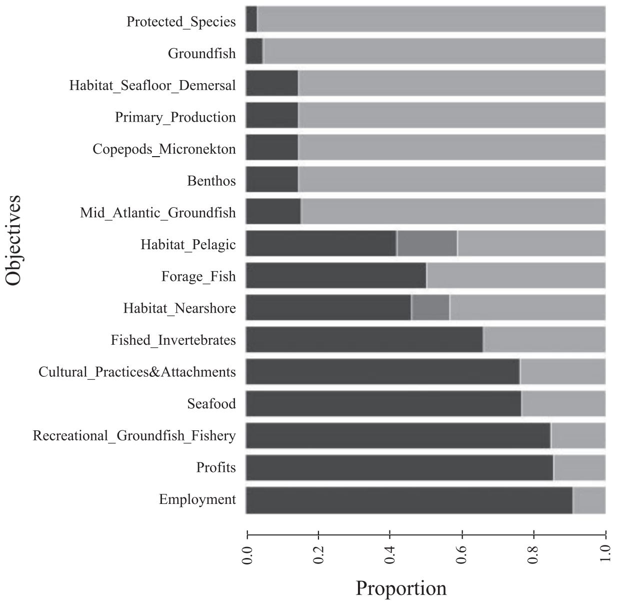

Figure 5. Qpress model results for a decrease in fishing pressure on forage fish in the Georges Bank ecoregion for the 1995–1999 scenario. Black = negative outcomes, light = positive outcomes, medium gray = neutral outcomes.

Table 3. Mental Modeler results comparing a single strategy (a decrease in pelagic fisheries) across two different time periods and ecosystems.

	Decreased Pelagic Fishery			
	Georges Bank		Gulf of Maine	
Objective	**1995-1999**	**2010–2014**	**1995–1999**	**2010–2014**
Pelagic Habitat	Neutral	Neutral	Neutral	Neutral
Nearshore Habitat	Neutral	Neutral	Positive	Positive
Seafloor & Demersal Habitat	Positive	Positive	Positive	Positive
Copepods & Micronekton	Positive	Neutral	Positive	Positive
Benthos	Positive	Positive	Neutral	Neutral
Forage Fish	Positive	Positive	Positive	Positive
Protected Species	Positive	Positive	Positive	Positive
Primary Production	Positive	Positive	Positive	Positive
Groundfish	Positive	Positive	Positive	Positive
Fished Invertebrates	Positive	Positive	Positive	Positive
Mid-Atlantic Groundfish	Positive	Positive	NA	NA
Recreational Groundfish Fishery	Negative	Negative	Negative	Negative
Cultural Practices & Attachments	Negative	Negative	Negative	Negative
Seafood	Negative	Negative	Negative	Negative
Employment	Negative	Negative	Negative	Negative
Profits	Negative	Negative	Positive	Positive

WGNARS used a multi-model approach for the MSE, employing three separate qualitative network modelling software packages: Mental Modeler (Kosko, 1986; Gray *et al.*, 2013), Qpress (Melbourne-Thomas *et al.*, 2012), and LoopAnalyst (Levins, 1974; Dambacher *et al.*, 2003; Justus, 2005), with the latter two implemented in R (R Development Core Team, 2015). Using multiple qualitative network modelling tools allowed WGNARS to evaluate the extent to which built-in constraints and assumptions in each package affected the MSE results. There are a number of margins on which comparison of MSE results are of interest. The first is comparing the same management strategy across environmental scenarios within the same modelling software, in this case Mental Modeler. Thus, for example, a decrease in the pelagic fishery in the Georges Bank 1995–1999 scenario resulted in different outcomes than a decrease in the pelagic fishery in the Georges Bank 2010–2014 scenario (Table 3). Whereas the decrease in fishing pressure resulted in nine desirable outcomes in the 1995–1999 scenarios, only eight desirable outcomes occurred using the same strategy in the 2010–2014 scenario. Although preliminary, these results underline the importance of system drivers on strategy outcomes.

The second margin of interest is comparing the same strategy and same scenario across different software packages. Figure 5 presents the results of the decrease in the pelagic fishery within the 1995–1999 scenario, as assessed through Qpress. As a stochastic software, the results of the decrease in fishing pressure are assessed through simulation, and Figure 5 presents the percentage of the 1000 simulations generating negative (black), neutral (dark gray) and positive (light gray) outcomes. In contrast to mental modeler, the impact of a decrease in fishing pressure on forage fish is indeterminate, with an equal number of positive and negative outcomes – likely due to the high levels of natural mortality. This differential impact on forage fish underlines the importance of multi-model inference, although more work is necessary in understanding how best to combine the outcomes of different models with respect to management advice.

A third margin of interest is assessing the same strategy across different ecoregions. Table 3 presents the Mental Modeler results for the decreased pelagic fishing pressure strategy for both the 1995–1999 and 2010–2014 scenarios in the Gulf of Maine ecoregion. The number of desirable outcomes is the same across scenarios in the Gulf of Maine, in contrast to the Georges Bank results. Thus, preliminary results suggest that the shift in underlying drivers is affecting each ecoregion differently. This highlights that the spatial resolution of the model is likely an important component of a system assessment, as these differences would not have been identified within the combined Georges Bank and Gulf of Maine model originally envisioned for this work.

Conclusions

This article provides an overview of three years of work (2014–2016) undertaken by WGNARS in support of IEA within the Northwest Atlantic Ocean, and the four phases of the workflow (Figure 1). WGNARS' shift from symposia to working meetings in 2013, supported by informal meetings throughout the year, proved critical for the development of the IEA. The working meeting improved trust and communication across disciplines, and provided for the development of a joint understanding of an integrated product. The use of support tables standardized the work in a manner that bolstered this trust in the process, and allowed subgroups to work independently on separate components of the IEA. In this manner, the larger group could be brought up to speed relatively quickly on the work being conducted by each subgroup.

The breadth of the undertaking necessitated the sacrifice of complexity across all disciplines and led to the current modelling approach. These types of models likely best serve a strategic role, such as gap analysis and risk assessment, rather than as a basis for tactical advice development. Although future work will focus on developing additional realism in the models, practical benefits have already been gleaned from the work (phase 4 of the workflow detailed in Figure 1). For example, the US conceptual models were presented as part of the Mid-Atlantic Fishery Management Council's Species Interactions Workshop in June 2015, and portions of the objectives were adopted by the New England Fishery Management Council's Risk Policy Working Group.

WGNARS' future work will focus on more integrated MSE scenarios, developing both communication and assessment best practices (particularly with regard to the use of qualitative data and models), and development of additional models. The core expertise lends itself to delving deeper into EBFM, as opposed to broadening the work into EBM, although issues of particular concern, such as pollution, will be considered in future iterations. This will allow for a more rigorous treatment of connections across theory and models, while navigating the different scales at which large-scale drivers, habitat, species, and humans function. Nevertheless, the WGNARS membership should be expanded beyond core membership to better represent likely tradeoffs associated with the management of both US and Canadian systems, an issue which has proven challenging in the past. Although the interest in pollution and energy development suggests expertise in issues such as toxicology, ocean chemistry, energy economics, acoustic pollution, and bioelectromagnetics are directions for further group expansion, the ultimate direction for expansion should be driven foremost by management needs, necessitating more direct manager engagement within WGNARS. Although this engagement would optimally include the direct weighting of objectives by managers, for a multitude of reasons managers have shown a historical reticence to developing objectives at this level of specificity. The current work suggests that IEAs can be relevant and informative in assessing trade-offs even absent these explicit weights.

Overall, WGNARS members found that trust and inclusivity were paramount in developing transdisciplinary work. Inclusivity was attained by providing multiple avenues for engagement, running the gamut from highly quantitative (indicator development and assessment), to fully qualitative (conceptual models) and intermediate (qualitative network models) products. Nevertheless, the complexity of the system indicates that certain tasks, such as risk assessments, will likely necessitate numeric modelling (including qualitative network models) since the number of interactions present in the system precludes reliance on expert opinion alone. Trust was developed through standardizing methodologies across disciplines and ensuring reproducibility of results (e.g. the conceptual model support table). Ultimately, it should be noted that transdisciplinary work is a slow process, and member engagement should thus be flexible in terms of commitment. Time (and money) is needed to build the group rapport critical in transdisciplinary work through repeated personal interactions. However, by allowing contributions from individuals in a less direct/less frequent manner, the work can draw from a much broader group of participants than would otherwise be possible.

Supplementary material

Supplementary material is available at the *ICESJMS* online version of the manuscript. Section 1 presents the objectives and indicators used in the WGNARS work. Section 2 presents an example of the WGNARS indicators scored against the WGECO/WGBIODIV indicator criteria, originally derived in support of the European Union's Marine Strategy Framework Directive.

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