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ARTICLE

Structural uncertainty in qualitative models for ecosystem-based management of Georges Bank

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Abstract: Quantitative models for marine ecosystem-based management are often constrained by availability of observations. Uncertainty about the underlying system structure can affect model estimates and conclusions about the consequences of management actions. Qualitative models can augment model development for decision-making and may provide an alternative to quantitative assessments. We apply qualitative loop analysis to assess the sensitivity of management outcomes to structural uncertainty within the Georges Bank social–ecological system. Loop analysis uses defined positive or negative relationships between system components to provide inference about cascading effects of pressures on components of management interest. We compare the sensitivity of outcomes from two management strategies in four model structures of the Georges Bank system that investigate trophic and socioeconomic model uncertainty. We summarize system responses to perturbation and compare these responses with a set of management objectives. Models with complex socioeconomic structure estimated positive outcomes more often but with less reliability than simpler models. Our analyses demonstrated trade-offs among habitat objectives for two management strategies, as well as uncertainty about the reliability of outcomes, contingent on model structure.

Résumé : Les modèles quantitatifs pour la gestion écosystémique en milieu marin sont souvent limités par les observations disponibles. L'incertitude concernant la structure sous-jacente au système peut avoir une incidence sur les estimations des modèles et les conclusions concernant les conséquences de mesures de gestion données. Des modèles qualitatifs peuvent être utiles au développement de modèles pour la prise de décisions et peuvent constituer une solution de rechange aux évaluations quantitatives. Nous utilisons l'analyse en boucle qualitative pour évaluer la sensibilité des résultats de gestion à l'incertitude structurelle au sein du système socioécologique du banc de Georges. L'analyse en boucle fait appel à des relations positives ou négatives définies entre différents éléments du système pour produire des inférences sur les effets en cascade de pressions sur des éléments d'intérêt pour la gestion. Nous avons comparé la sensibilité des résultats pour deux stratégies de gestion dans quatre structures de modèle du système du banc de Georges qui examinent l'incertitude de modèles trophiques et socioéconomiques. Nous résumons les réactions du système à la perturbation et comparons ces réactions à un ensemble d'objectifs de gestion. Les estimations de modèles caractérisés par une structure socioéconomique complexe produisent des résultats positifs plus souvent mais de manière moins fiable que les modèles plus simples. Nos analyses font ressortir des compromis entre différents objectifs liés aux habitats pour deux stratégies de gestion, ainsi que l'incertitude associée à la fiabilité des résultats, selon la structure du modèle. [Traduit par la Rédaction]

Introduction

Marine ecosystem-based management requires a broad perspective to make informed decisions related to multiple social, economic, and environmental objectives (Mangel et al. 1996; Endter-Wada et al. 1998; Leslie and McLeod 2007; Fulton et al. 2014). Data-driven models have been developed to explore ecosystem approaches to fisheries management, but few have been implemented in final management decisions (Skern-Mauritzen et al. 2016). Fewer still are applied to multiple uses of marine resources and their cumulative impacts on species or habitats of interest (e.g., Link et al. 2008*b*, 2010; Fulton et al. 2011*b*; Guerry et al. 2012). All ecosystem-based modeling efforts encounter barriers related to data availability, particularly data gaps related to nonfocal functional groups or the human dimensions of social–ecological systems (Atkins et al. 2011; Griffith and Fulton 2014). Heterogeneity in data availability across disciplines leads to simplifying assumptions in ecosystem models, which can affect understanding of system function and may ultimately lead to inaccurate estimates of future states (Keyl and Wolff 2008; Fulton et al. 2011*a*). These assumptions include, in part, the functional relationships between system components and the parameter values used in these functions. Rigorous model development tests the sensitivity of these assumptions (e.g., Lehuta et al. 2010), yet implicit in these assumptions is the structure and number of relationships among system components. Often, model assumptions simplify the unknown complexity of system components for which data are unavailable. Thus, the combination of model scope and detail, functional forms, and parameter values leads to structural uncertainty in models of social–ecological systems (Fulton et al. 2003; Link et al. 2012). This structural uncertainty ultimately presents a trade-off between model predictive ability and realistic complexity (Collie et al. 2016), which has limited the ability for social–ecological models to provide advice for ecosystem-based management decisions.

Management advice often must be provided before additional data can be collected to clarify and support system structural assumptions (Harwood and Stokes 2003; Nichols and Williams 2006; Halpern et al. 2006). Considering the scale and complexity

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of marine social–ecological systems, multi-objective ecosystem-based management decisions are inevitably data-limited (Cooney 2004; deYoung et al. 2004). Qualitative methods provide the ability to assess the impacts of structural uncertainty on the understanding of a modeled system's behavior (Hosack et al. 2008; Nuttle et al. 2009; Novak et al. 2011; Melbourne-Thomas et al. 2012). Simple qualitative models of appropriate scope for ecosystem-based management can be constructed to evaluate the influences of structural uncertainty (i.e., number of interactions) and complexity (i.e., number of modeled components) without the need to choose among functional forms or estimate parameters. These influences should be evaluated in any ecosystem model, quantitative or qualitative, as they impact our understanding of the managed system and its response to potential management actions (Fulton et al. 2003).

Qualitative loop analysis (Levins 1974; Puccia and Levins 1985; Dambacher et al. 2002) provides a simple approach to evaluate the influences of structural uncertainty in qualitative ecosystem-based models. Loop analysis relies on information about the presence of interactions among system components and the positive or negative influence of interactions on affected components without quantitative data requirements (Levins 1974; Puccia and Levins 1985). Rather than focusing on known or expected direct effects, qualitative loop analysis follows the pathways through which influences cascade in a system, allowing managers to see the overall indirect effects of a change in one or more components on the rest of the system (Dambacher et al. 2002; Justus 2006). Although loop analysis has often been applied to models of trophic structure (Dambacher et al. 2002; Ortiz and Wolff 2002; Reum et al. 2015), the approach may be applicable to larger social–ecological systems for ecosystem-based management (Dambacher et al. 2009; Lassalle et al. 2014; Carey et al. 2014).

Here we apply qualitative loop analysis to a conceptual model of the Georges Bank social–ecological system compiled by the International Council for the Exploration of the Sea (ICES) Working Group on the Northwest Atlantic Regional Sea (WGNARS) to understand the effects of structural uncertainty and complexity on management objectives. The WGNARS conceptual model summarizes the physical, ecological, and socioeconomic drivers in the Georges Bank system to aid ecosystem-based fisheries management in the region (WGNARS 2016; DePiper et al. 2017), including multiple ecological and social objectives. Our investigation focuses on simplifying assumptions related to the structure of the food web and complexity of the fishery on Georges Bank. We test the sensitivity of management outcomes to variations in system structure, using four models with combinations of simple versus complex fishery structure and reduced versus detailed trophic structure. We implement loop analysis to demonstrate (*i*) the ability to investigate the dynamics of the Georges Bank social–ecological system using qualitative models, (*ii*) expected trade-offs among potentially conflicting ecosystem-based management objectives, and (*iii*) the effects of uncertainty in system structure on model outcomes and associated management implications.

Methods

Loop analysis

The WGNARS conceptual model of the Georges Bank system consists of three subsystems (environmental, ecological, and socioeconomic), each containing state nodes that interact within and among subsystems (DePiper et al. 2017; Fig. 1). The environmental subsystem influences the fisheries and ecological habitats without feedback from the rest of the system. The ecological subsystem is composed of habitats, focal (managed) species groups, and basal functional groups that support the food web. The socioeconomic subsystem contains the commercial and recreational fisheries that interact with focal species groups and habitats on Georges Bank. In addition to fisheries and their related indicator nodes, the socioeconomic subsystem contains a "Cultural Practices & Attachments" node representing the coastal communities tied to Georges Bank's natural resources, similar to "sense of place" in other social–ecological conceptual models (Harvey et al. 2016). WGNARS prioritized resolution in the trophic interactions between managed species and the rest of the ecological system and differences between recreational and commercial fisheries during construction of the model (WGNARS 2016). Although the conceptual model does not represent every resource or human use of Georges Bank, it reflects the scope of expertise of the WGNARS group and contains the detail needed to investigate questions related to ecosystem-based fisheries management trade-offs in the system (WGNARS 2016; DePiper et al. 2017).

We applied qualitative loop analysis (Levins 1974; Dambacher et al. 2003*b*) to the WGNARS conceptual model of the Georges Bank social–ecological system (WGNARS 2016) by adapting the network into a signed digraph (Fig. 1). The signed digraph can be represented as a square community matrix (**A**; Levins 1974) with each column indicating the linear effect of a component on the other system components in each row according to the defined positive (+1), negative (–1), or neutral (0) interactions. Stable ecological systems dampen perturbations via negative feedback loops and settle toward an equilibrium state if there is negative overall feedback within the system, indicated by a positive determinant of the negative community matrix (Dambacher et al. 2002). For example:

$$\mathbf{A} = \begin{bmatrix} -1 & +1 & 0 \\ -1 & -1 & +1 \\ 0 & 0 & -1 \end{bmatrix}, \quad \det(-\mathbf{A}) = 2$$

Local or neutral stability may occur if the real parts of the community matrix eigenvalues are less than or equal to zero (Dambacher et al. 2003*a*). Negative self-regulation of all elements was imposed in the Georges Bank community matrix to encourage stable equilibrium of the system (i.e., all diagonal elements of the community matrix were assigned a value of –1; Justus 2005).

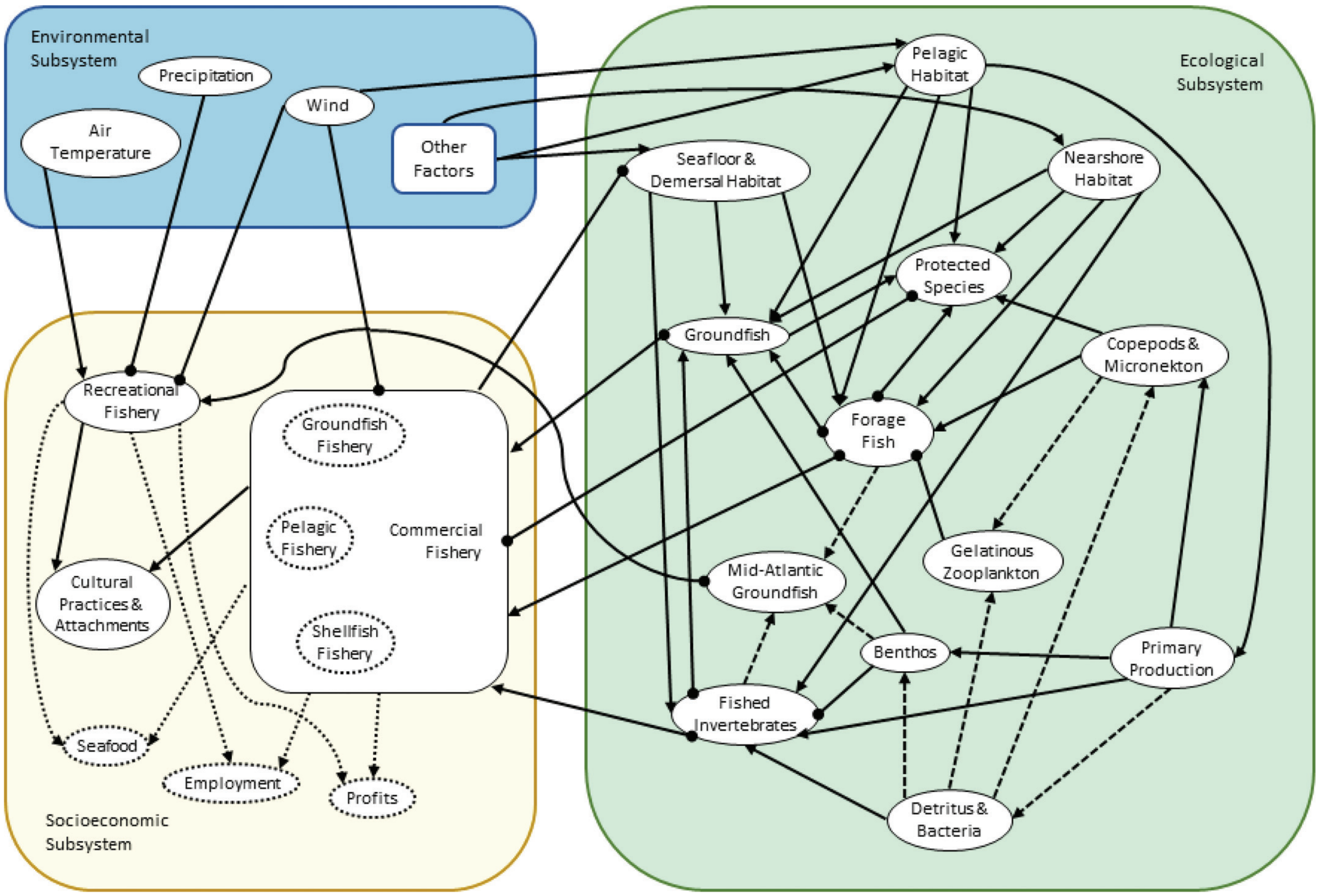
The negative inverse of the community matrix ($-\mathbf{A}^{-1}$) expresses the change in equilibrium state for each system component given a sustained, or "press," perturbation (e.g., increased carrying capacity or total allowable catch (TAC); Nakajima 1992; Dambacher et al. 2002, 2003*b*). By assuming the system is stable, qualitative press perturbations from the negative inverse community matrix can also be derived as the adjoint of the negative community matrix (Dambacher et al. 2002). Using the example above:

$$\text{adjoint}(-\mathbf{A}) = -\mathbf{A}^{-1}\det(-\mathbf{A}) = \begin{bmatrix} 1 & 1 & 1 \\ -1 & 1 & 1 \\ 0 & 0 & 2 \end{bmatrix}$$

These press perturbations reflect the influence of a sustained marginal increase in a chosen component on each of the other components of the matrix (Dambacher et al. 2002, 2003*b*). Here, changes in system components are expressed relative to some unspecified equilibrium level and do not rely on estimates of current states (e.g., biomass). Rather, a linear trend between each interacting component is assumed to reflect the direction of a response but not the magnitude of that response. For a detailed description of the definitions and concepts, we refer readers to Dambacher et al. (2002, 2003*b*).

We used the LoopAnalyst package in R (Dinno 2015; R Core Team 2015) to calculate press perturbations of the Georges Bank system. The values in the resulting adjoint matrix indicate the net feedback (positive or negative) that the system has on the row components given an increase in the column component. These net responses are a result of the number of feedback loops in the

Fig. 1. Modified signed digraph of the Georges Bank social–ecological system with environmental (blue), ecological (green), and socioeconomic (yellow) subsystems. Links ending in arrows indicate a positive interaction, and links ending in circles indicate negative interactions. Links connected to rounded rectangles (Other Factors and Commercial Fishery) indicate multiple fine-scale interactions between nodes (not shown). The model formulation for the Simple socioeconomic subsystem (assuming the enclosing Commercial Fishery box serves as a node) and Reduced trophic structure is shown with solid node and link lines. The alternative Complex socioeconomic structure is indicated by additional nodes and links with dotted lines. Dashed links indicate additional interactions in the Detailed trophic model. See online Supplementary Material[1] (spreadsheet: Community matrices) for full model structures. [Colour online.]



network and the signs of the interactions forming the loops. The weighted feedback matrix summarizes the reliability of the estimated responses (Dambacher et al. 2002). We calculated the weighted feedback matrix as the absolute value of the adjoint matrix elements for each component pair in the Georges Bank system divided by the total number of feedback loops (**T**) linking them (Dambacher et al. 2002, 2003*a*; Dinno 2015):

$$\mathbf{W} = \frac{\overrightarrow{|\text{adjoint}(-\mathbf{A})|}}{\mathbf{T}}$$

where the arrow indicates element-by-element division. Values below 0.5 in the weighted feedback matrix, or reliability weights, indicate a large proportion of pathways with conflicting sign affecting a component, resulting in uncertainty about the affected component's cumulative response to perturbation.

Structural uncertainty

During development of the conceptual model, the WGNARS group chose to reduce the number of links included in the model to focus on interactions with managed species groups and to represent a more complex socioeconomic subsystem to address multiple indicators of human well-being (WGNARS 2016; DePiper et al. 2017). We view the result of these decisions as one of many potential hypotheses about the Georges Bank system. To test sensitivity of press perturbation outcomes to these decisions, we developed two ecological subsystem models: (1) a "Reduced" trophic structure, reflecting the decision to focus on managed species trophic interactions (solid links in Fig. 1), and (2) a "Detailed" trophic structure, which includes additional predation interactions on nonfocal species (dashed links in Fig. 1). We also defined two socioeconomic subsystem models: (1) a "Simple" socioeconomic subsystem, which represents a single commercial fishery and does not include indicator nodes for employment, profits, and seafood provision (solid nodes in Fig. 1), and (2) a "Complex" socioeconomic subsystem outlined by WGNARS, including three selective commercial fisheries that produce profits, seafood, and employment within coastal communities (dotted nodes in Fig. 1). These socioeconomic models reflect simplistic structures of previous ecosystem models applied to the region (Link et al. 2008*a*; Gamble and Link 2009; Gaichas et al. 2017). We combined the alternative subsystem models in a 2 × 2 crossed experimental

[1]Supplementary data are available with the article through the journal Web site at http://nrcresearchpress.com/doi/suppl/10.1139/cjfas-2017-0149.

Table 1. Summary of ICES Working Group on the Northwest Atlantic Regional Sea (WGNARS) objectives and corresponding community matrix components with their desired perturbation trend interpretations.

Objective	System component	Desired trend
Improved recreational opportunities	Recreational groundfish fishery	+
Optimized food production*	Seafood	+ or 0
Increased employment*	Employment	+
Increased profits*	Profits	+
Increased threatened, endangered, and protected species biomass	Protected species	+
Increased groundfish biomass	Groundfish	+
Increased forage fish biomass	Forage fish	+
Increased fished invertebrate biomass	Fished invertebrates	+
Maintenance of pelagic habitat	Habitat: pelagic	+ or 0
Maintenance of nearshore habitat	Habitat: nearshore	+ or 0
Maintenance of demersal and seafloor habitat	Habitat: seafloor and demersal	+ or 0
Improved human well-being	Cultural practices and attachments	+

Note: Objectives indicated with an asterisk (*) were assessed via the Commercial Fishery component in models with the Simple socioeconomic subsystem.

design, resulting in four system models (fully specified community matrices are provided in the online Supplementary Material spreadsheet: Community Matrices[1]). Thus, we tested the effect of structural connectivity (Reduced versus Detailed) and socioeconomic complexity (Simple versus Complex) on the dynamics of the Georges Bank system.

Sensitivity of management outcomes

To assess sensitivity of the four model structures, we compared the expected outcomes from press perturbations of each model for two potential management strategies: (1) increased commercial fishing and (2) increased energy production. The effects of increased commercial fishing were evaluated from the press perturbation of the “Commercial Fishery” node in Simple socioeconomic models. Increased commercial fishing in Complex models was calculated as the sum of the adjoint matrix elements across rows of three fishery nodes: Commercial Groundfish Fishery, Commercial Pelagic Fishery, and Commercial Shellfish Fishery (Dambacher et al. 2003*b*). While this additive approach magnifies the uncertainty of the results provided by the Complex models, we viewed this step as necessary to compare the model structures from a common baseline. Results of increasing the targeted fishery nodes individually are provided in the online Supplementary Material (spreadsheet: Strategies; also see Fig. S1[1]). To represent increased energy production, we assumed a reduction in the Nearshore Habitat and Seafloor & Demersal Habitat nodes. Although the WGNARS model was originally formulated to assess ecosystem-based fishery management questions, we implemented this strategy to evaluate the ability of these models to assess effects of multiple resource uses. We assumed energy production would result in initial disruption of supporting services provided by these habitats, as well as permanently reduce the area available to provide these services, resulting in a new equilibrium state (Atkins et al. 2011). Infrastructure related to energy production can provide additional habitat, but we preferred to take a precautionary approach in our initial evaluation (Inger et al. 2009). Reduced pressures for this scenario were derived by changing the sign of the sum of adjoint matrix elements in the appropriate columns for these two habitat nodes (Dambacher et al. 2002, 2003*b*).

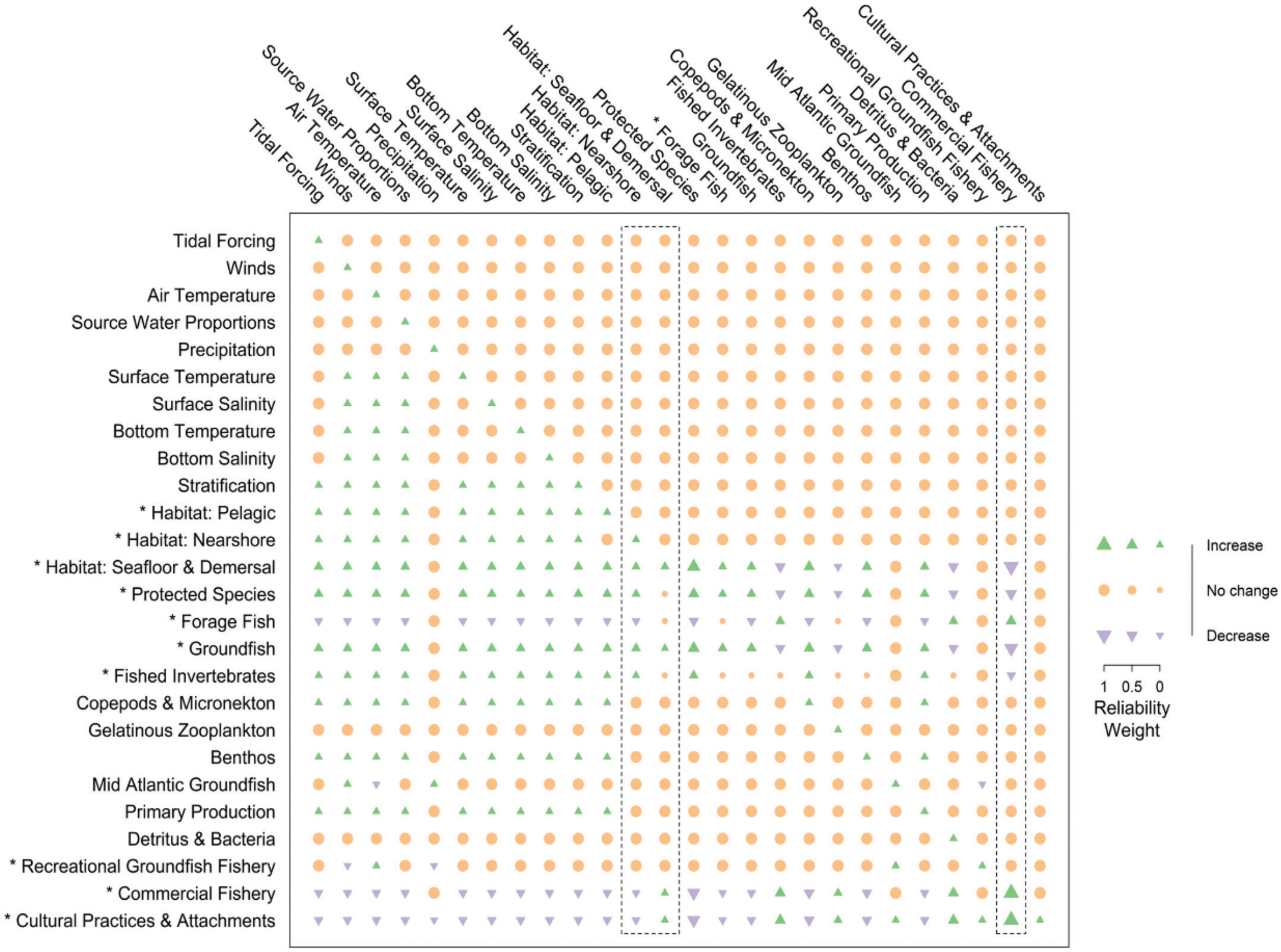
For the four model structures and two management strategies, we compared the qualitative trend of effected indicator nodes with the WGNARS objectives of food production, employment, profits, recreation, habitat maintenance, rebuilding of focal stock biomasses, and improved human well-being (Table 1). Management strategies were interpreted as achieving a WGNARS objective of improving a system component if the associated indicator component showed a positive impact of the management strategy. Successful maintenance of a system component was interpreted as a neutral (0) or positive effect of a management strategy. For Simple socioeconomic models, we assumed that the Commercial Fishery node acted as a proxy for the indicator nodes for Profits, Employment, and Seafood production, which were removed from Simple model structures. This may be a reasonable assumption given the positive interactions between these nodes in the more explicit Complex subsystem structure. Finally, outcomes for the WGNARS objectives were scaled by the weighted feedback values from each model structure to reflect the reliability of these predictions, with values closer to one being considered more reliable.

Results

Both Simple model structures were determined to be stable (det(–**A**) = 6), while the Complex model structures were neutrally stable (det(–**A**) = 0). We include the results of the Complex models here as a demonstration and note that any result will likely be susceptible to external factors (Dambacher et al. 2002). The qualitative responses of press perturbation for the Simple Reduced model are provided in Fig. 2 as an example, with the remaining three models provided in the online Supplementary Material (spreadsheet: Adjoint matrices)[1]. Nodes in the environmental subsystem were not affected by those in the ecological or socioeconomic subsystems because there are no feedbacks to the environmental subsystem in the models. Pelagic Habitat and Nearshore Habitat were unresponsive to biogenic and human disturbances across models, in contrast with the Seafloor & Demersal Habitat node, which was impacted by perturbations to several nodes. Across models, nodes with more interactions within the ecological and socioeconomic subsystems displayed both positive and negative impacts depending on the perturbed node (e.g., columns in the response matrix; Fig. 2). One notable difference between models was the positive response of Gelatinous Zooplankton and Detritus & Bacteria nodes to press perturbation of lower trophic levels in the Simple Detailed model, which contrasted with estimated neutral responses in Reduced trophic models (Supplementary Material spreadsheet: Adjoint matrices[1]).

Nearly half of all interactions in each of the models had low reliability weights (≤0.5) for node responses to perturbations, particularly in Complex models, a symptom of community matrices with many nodes (Dambacher et al. 2003*a*; Dambacher and Ramos-Jiliberto 2007). The press perturbations of the Seafloor & Demersal Habitat and Commercial Shellfish Fishery nodes in Complex models were highly uncertain, with press perturbation responses and reliability weights equal to zero, signifying equal evidence for both positive and negative effects of these highly connected components (Supplementary Material spreadsheet:

Fig. 2. Matrix of estimated press perturbation responses for individual components in the Simple Reduced model of the Georges Bank social–ecological system. Icons indicate the direction of change as increasing (triangle), decreasing (upside-down triangle), or no change (circle) and range in size according to the reliability weight from the loop analysis, with larger icons (1) indicating more reliable responses than smaller icons (0). Columns within dashed boxes contain the responses of each system component to the two management strategies (increased energy production on the left, increased fishing on the right), with indicator variables marked with an asterisk (*). [Colour online.]



Strategies[1]). Some node responses were more reliably estimated, for example negative impacts of the Commercial Fishery on Groundfish and Seafloor & Demersal Habitat in the Simple models. We assumed neutral effects had a reliability weight of 1 for nodes not included in the paths of pressed nodes (Dambacher et al. 2002).

Increased commercial fishing and increased energy production had similar effects on management objectives (Fig. 3). In Simple models, increased energy production was estimated to negatively impact nearshore habitat, whereas increased commercial fishing did not impact this component in any model considered. This trade-off between negative versus neutral effects in the Simple models resulted in more management objectives being achieved under an increased fishing management strategy (Table 2). Complex models estimated more achieved outcomes than Simple models, predicting maintenance of nearshore habitat under energy production and improved fished invertebrate stocks under both strategies (Fig. 3). Including Detailed interactions in the ecological subsystem led to estimates of improved recreational opportunities regardless of management strategy. Both management strategies failed to meet the objectives of improving groundfish and protected species stocks, as well as maintaining demersal habitat.

Additional trophic detail had little impact on management outcome reliability, although estimates for the human well-being objectives were more reliable in Reduced trophic models, and recreational fishing was expected to increase in Detailed trophic models (Fig. 3). Simple models had more reliably estimated responses to management strategies than Complex models, largely due to the effect of additive press perturbation on the reliability weights of estimated outcomes. Responses from increased fishing in Simple models had the highest reliability weights because these responses were derived from a single press perturbation. The impacts of fishing in Complex models were summed across the three targeted fishery nodes, including the Commercial Shellfish Fishery, which had equal numbers of estimated positive and negative feedbacks from press perturbation. This diluted the estimated reliability of the responses to increases in the Commercial Groundfish Fishery and the Commercial Pelagic Fishery, which both had similar outcomes to the aggregated estimates for this management strategy (Fig. S1[1]). Similarly, reliability estimates for the increased energy production strategy were calculated across two press perturbations (Nearshore Habitat and Seafloor & Demersal Habitat), resulting in lower reliability weights. Again, highly unreliable responses in the Seafloor & Demersal Habitat press perturbation diluted the effects of Nearshore Habitat loss. Across

Fig. 3. Summarized outcomes of two management strategies against 12 ecosystem-based management objectives for Georges Bank. Seafood, employment, and profits objective outcomes (*) in Simple models are assumed responses from increases to the Commercial Fishery node. The size of each outcome icon reflects the weighted feedback value calculated for each indicator node, with values below 0.5 considered unreliable response estimates. [Colour online.]

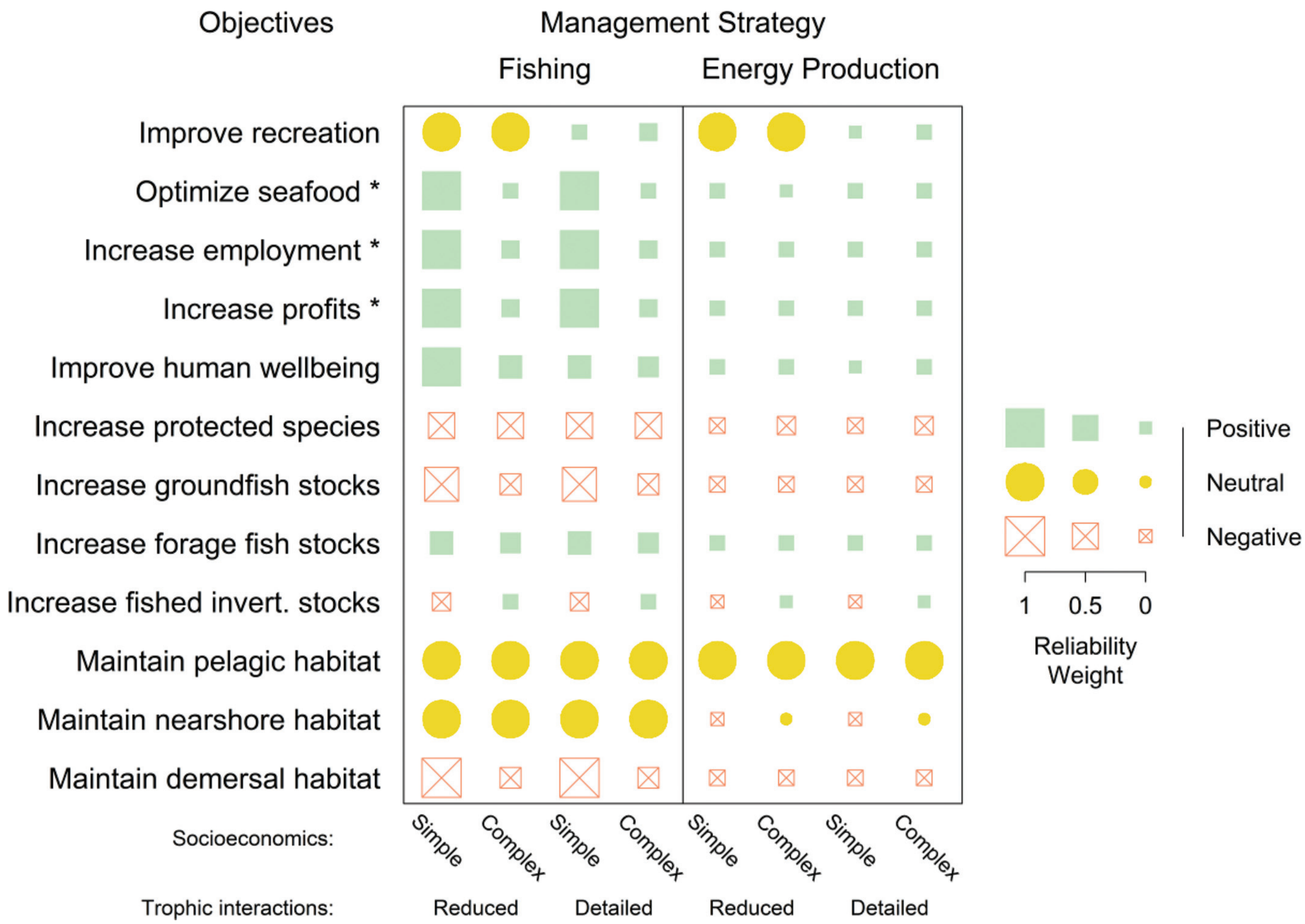


Table 2. Summary of cumulative outcomes from two management strategies across four model structures in terms of the total number (proportion in parentheses) of estimated achieved or unachieved objectives.

	Increased fishing		Increased energy production	
Model	Achieved	Unachieved	Achieved	Unachieved
Simple Reduced	8 (0.67)	4 (0.33)	7 (0.58)	5 (0.42)
Complex Reduced	9 (0.75)	3 (0.25)	9 (0.75)	3 (0.25)
Simple Detailed	8 (0.67)	4 (0.33)	7 (0.58)	5 (0.42)
Complex Detailed	9 (0.75)	3 (0.25)	9 (0.75)	3 (0.25)
All models				
Raw total	34	14	32	16
Weighted average	8.5	3.5	8	4

all models, the responses to energy production were less reliable than those estimated from increased fishing.

Discussion

Uncertainty and multimodel inference

Using qualitative loop analysis, we showed that model structure affects estimates of ecosystem-based management outcomes. These effects are due to uncertainty in both structural complexity and connectivity. Adding complexity to the socioeconomic subsystem changed the estimated direction of a management strategy's impact, particularly for fished invertebrates and nearshore habitats. Although the addition of nodes for economic and social drivers, such as employment and profits, better reflects the reality of the Georges Bank social–ecological system, managers must be aware of the effects these additions may have on modeled outcomes. Conversely, simpler models with fewer nodes depicted greater trade-offs among objectives for the management strategies we explored. We emphasize that our study shows that addition of these factors affects the behavior of model dynamics, yet the true response of the Georges Bank system to either strategy remains highly uncertain. Because the WGNARS model was primarily intended to evaluate fisheries management strategies, the simplifying assumptions about energy production in this study likely do not reflect the full range of system responses related to this activity.

In addition to uncertainty between model structures, there was high uncertainty about the direction of responses to management within models. Low weighted feedback values reflect contradicting feedback loops leading to each node of concern (Dambacher et al. 2003*b*). This result is not surprising considering that the addition of interactions (i.e., increasing connectivity) and nodes increases the number and length of feedback loops in a particular system (Dambacher et al. 2003*a*). Assumed linear and additive in this application, the responses at each step in a feedback loop are subject to further uncertainty about the shape, sign, magnitude, and natural variation in each response (Dambacher et al. 2002; Justus 2006). An additional source of low reliability in outcomes is the calculation of multiple press perturbations, which additively increases uncertainty (Dambacher et al. 2002, 2003*b*). This effect contributed to the uncertainty of our Complex models because weights were calculated over three nodes (commercial pelagic, groundfish, and shellfish fishery nodes), whereas a single commercial fishery node was used for the Simple model analyses. This additive method obscured the completely uncertain effects of increased shellfish fishing and decreased seafloor habitat in Complex models. These cumulative uncertainties within and across models in our study likely indicate the need for a more refined model structure to better represent the true system dynamics (Holsman et al. 2017).

Models with simple socioeconomic systems allowed for high reliability weights for most indicators of concern. However, these weights may be prone to bias, which can be uncovered by comparison with more complex model structures (Collie et al. 2016). Our investigation of more complex socioeconomic systems revealed that fished invertebrate stocks and nearshore habitats may be less impacted by human activities than was indicated by simpler models, despite the added uncertainty surrounding these dynamics. The model structures assessed here provide managers with a set of assumptions to test as they construct quantitative models of the Georges Bank system. The reliability of qualitative model responses may also be corroborated through comparison with empirical time series or by using an operating model reflecting these sources of uncertainty in an ecosystem-level management strategy evaluation (Bunnefeld et al. 2011; Lassalle et al. 2014).

Rather than emphasizing reliability of responses in any single model, multimodel inference from many qualitative loop analyses provides a more general understanding of system dynamics (Rehme et al. 2011). Cross-model comparisons can provide context to management decisions when general agreement in the responses of system components exists across models. In contrast, when a management strategy results in differing responses among model structures, as seen for fished invertebrates in our investigation (Fig. 3), these diverging results can indicate which management objectives are related to uncertain dynamics and may be highly sensitive to any management action. The multilevel assessment of uncertainty presented here can help assessment scientists and managers tease apart the effects of uncertainty due to model structure rather than uncertainty about the response of system components to management.

Management strategy trade-offs

In addition to understanding ecosystem dynamics, a multimodel perspective allows us to assess trade-offs between management strategies and a defined set of objectives. We found that both management strategies were generally beneficial for the socioeconomic objectives of optimized seafood production, increased employment and profits, improved recreational opportunities, and improved human well-being (Fig. 3). This agreement between models and management strategies may be due in part to socioeconomic drivers prioritizing strategies that would fulfill these objectives, but more likely because of the simplified model representation of these factors. In reality, the socioeconomic subsystem is more complicated than that reflected by our chosen analytical method. A reduced fishing effort strategy can be derived by changing the sign of each positive or negative effect in the appropriate column(s) of the matrices in Figs. 2 and 3 (e.g., green icons become red in Fig. 3; see online version for colour), resulting in a uniform negative impact of decreased fishing for all socioeconomic objectives. Similarly, the ecological objectives relating to species stocks and habitats showed little sensitivity to the strategies explored here. This may indicate a true trade-off between socioeconomic and ecological objectives, or it may indicate an inability of qualitative loop analysis to reflect fine-scale dynamics within the modeled system. Given this trade-off as presented by our qualitative approach, managers might, for example, decide between the possible strategies based on prioritization of the management objectives (e.g., Mardle et al. 2004; see also Kiker et al. 2005; Huang et al. 2011), or they may choose to further consider a strategy based on the predictability of its outcome in an adaptive management context (Armitage et al. 2009). Managers may also conduct further risk analyses to directly investigate the particular effects of management on an uncertain indicator node (Fletcher 2005; Holsman et al. 2017).

Loop analysis of social–ecological systems

While our qualitative models make simplifying assumptions about system interactions, they paint a relatively complex picture of the dynamics of the Georges Bank social–ecological system. We were able to represent heuristic links between system components to assess qualitative trends in the system in response to various management actions. With this approach, we circumvented many of the uncertainties (e.g., observation error, parametric error, variable functional responses) that plague quantitative ecosystem models. These methods offer a framework to evaluate uncertainty rapidly across a range of system components about which data and understanding are often highly variable, even for the well-studied Georges Bank system. Loop analysis and similar techniques have already been used to describe interactions in human-impacted ecosystems (Ortiz and Wolff 2002; Raymond et al. 2011; Lassalle et al. 2014) and to evaluate ecosystem effects of management actions (Carey et al. 2014; Reum et al. 2015; Harvey et al. 2016). There is also guidance for how to group interacting species in an ecosystem when applying these approaches (Raick et al. 2006; Aumann 2007; Metcalf et al. 2008). These guidelines draw from ecological theory and can help bound the flexibility of qualitative model development in systems where little is known about the ecosystem's structure or function.

Qualitative loop analysis is also flexible in the methods through which system components are linked to each other and to management objectives. Because the relationships defined in the community matrix are unitless, we were able to link subsystems with differing "currencies", such as groundfish biomass to fishery catch and (or) effort and then to employment. This flexibility also helped in linking indicator nodes to management objectives. Although thoughtful operational objectives are beneficial for ecosystem-based management (Slocombe 1998), it is often difficult to specify quantitative thresholds, or even units, for all objectives. For example, although the WGNARS group identified maintenance of habitat quality as an objective from existing regional documents (WGNARS 2015), not enough detail was provided to create measurable indices or thresholds for marine habitats on Georges Bank. The loop analysis described here foregoes these restrictions and equates an increase or neutral response in the Nearshore Habitat node with achievement of the habitat maintenance objective. The same logic applies to socioeconomic objectives: What level of employment or profits is adequate? By focusing on direction of responses, our approach provides useful guidance about management outcomes without the need to identify thresholds or levels for these complex and politically charged questions. Thus, the benefits and applicability of qualitative loop analysis to data-limited as well as data-rich social–ecological systems becomes clear.

We have demonstrated the ease and applicability of qualitative loop analysis to inform management of marine social–ecological systems, as well as its limitations. This application reveals trade-offs among management objectives and between potential management strategies, highlights the effects of structural uncertainty and model complexity on management advice, and reflects the ecological processes expected of a complex dynamic system. Further, counterintuitive results draw attention to data gaps where structural uncertainty and system dynamics interact and where more detailed, quantitative investigation may be warranted. The qualitative methods we explore here provide insight about potential risks to ecological and socioeconomic objectives and advance integrated ecosystem assessment of the Georges Bank marine system.

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