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Linking ecosystem processes to communities of practice through commercially fished species in the Gulf of Alaska

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Marine ecosystems are complex, and there is increasing recognition that environmental, ecological, and human systems are linked inextricably in coastal regions. The purpose of this article was to integrate environmental, ecological and human dimensions information important for fisheries management into a common analytical framework. We then used the framework to examine the linkages between these traditionally separate subject areas. We focused on synthesis of linkages between the Gulf of Alaska marine ecosystem and human communities of practice, defined as different fisheries sectors. Our specific objective was to document the individual directional linkages among environmental, ecological, and human dimensions variables in conceptual models, then build qualitative network models to perform simulation analyses to test how bottom-up and top-down perturbations might propagate through these linkages. We found that it is both possible and beneficial to integrate environmental, ecological, and human dimensions information important for fisheries into a common framework. First, the conceptual models allowed us to synthesize information across a broad array of data types, representing disciplines such as ecology and economics that are more commonly investigated separately, often with distinct methods. Second, the qualitative network analysis demonstrated how ecological signals can propagate to human communities, and how fishery management measures may influence the system. Third, we found that incorporating multi-species interactions changed outcomes because the merged model reversed some of the ecological and human outcomes compared with single species analyses. Overall, we demonstrated the value of linking information from the natural and social sciences to better understand complex social–ecological systems, and the value of incorporating ecosystem-level processes into a traditionally single species management framework. We advocate for conceptual and qualitative network modelling as efficient foundational steps to inform ecosystem-based fisheries management.

Keywords: conceptual model, ecosystem-based fisheries management, Gulf of Alaska, human dimensions, qualitative network model.

Introduction

Marine ecosystems are complex, and there is increasing recognition and evidence that environmental, ecological, and human systems are linked inextricably (e.g. Perry *et al.*, 2010; Pollnac *et al.*, 2010). Conceptual frameworks, such as the social–ecological systems framework (Ostrom, 2009), assist with identifying relevant components of such systems. Understanding linkages between climate, ecosystems, and people is important because they affect each other through feedback loops (Liu *et al.*, 2007; Collins *et al.*, 2011). For instance, if fish stocks decline because of changing oceanographic conditions (bottom-up forcing), fishermen might fish harder to maintain their income (top-down forcing), further degrading fish stocks. An integrated evaluation of linkages between biophysical and social aspects in the marine environment at a management-relevant scale can guide managers to explicitly consider them in their decision-making, ideally leading to desirable social and ecological outcomes (Armitage *et al.*, 2009).

Fisheries management still predominantly focuses on single-species management of commercially important species, with some advances towards ecosystem-based (fishery) management (Link and Browman, 2014). Single-species fisheries management is prevalent because management structures and stock assessment models, and indeed much of fisheries science, have developed to support this approach (DiCosimo *et al.*, 2010; Methot *et al.*, 2014). Aspects of ecosystem-based approaches have been incorporated into single-species approaches, e.g. adding quotas for bycatch species to help reduce the effects of fishing on vulnerable ecosystem components (Witherell and Pautzke, 1997; Witherell *et al.*, 2000). In some US regions, fishery managers review ecosystem indicators annually to understand the context for single species management and are developing methods for addressing species, climate, human, and other ecosystem interactions (e.g. Gaichas *et al.*, 2016; Zador *et al.*, 2017). Yet, more complete ecosystem-based approaches have yet to be commonly implemented (Arkema *et al.*, 2006), partly because of data limitations, and few to date formally integrate social–ecological linkages.

Another complexity of fisheries management is the many types of fishing communities and their differing interactions with the environment. Generally, there are two types of fishing communities that fisheries managers must take into consideration. In the more traditional sense of community, "communities of place" are defined by a geographic location, such as fishing villages. However, fisheries managers must also consider "communities of practice". Broadly, communities of practice are groups of individuals that participate in the same activity, have a shared repertoire, and through their participation, engage in discussions and joint activities that foster collective learning (adapted from Wenger, 1998).

Here, we operationalize the concept of community of practice in the realm of fisheries: a collective group of individual fishers that use the same gear type to target the same species, and regularly interact by sharing information and having discussions related to the practice and management of their particular fishery. We can categorize such communities principally by the species they target, followed by the community's participation in the commercial, recreational, and subsistence fishery of the target species, each of which can be by economic values, management priorities, and interactions within a given ecosystem. The examination of communities of practice is particularly relevant for commercial and recreational fisheries when fishers come from many diverse geographic locations to participate in the same fishery (Martin and Hall-Arber, 2008). Focusing on communities of practice allows our analysis to map changes in species-specific environmental and ecological interactions with fleets and gear-types. In contrast, communities of place are often involved in many different commercial, recreational and subsistence fisheries, and thus may include expanded and non-overlapping environmental and ecological components

Efforts are underway to include nuances of human dimensions into fisheries assessments and management. For example, specific initiatives aiming to integrate human dimensions into Integrated Ecosystem Assessments (IEAs) are in progress internationally (e.g. ICES, 2015). In the United States, IEAs provide a framework for addressing ecological and human dimensions holistically (Levin *et al.*, 2009, 2014). The process of integrating ecological and human dimensions in IEA development is evolving in many regions, including the Northeast United States and Canada (DePiper *et al.*, 2017). In Alaska (United States), the human dimension is currently incorporated into indicator-based ecosystem assessments, economic status reports, as well as more in-depth social impact assessments of proposed management changes (Downs and Weidlich, 2016; Fissel *et al.*, 2016; Himes-Cornell and Kasperski, 2016; Kasperski *et al.*, 2016; Zador *et al.*, 2017). For example, two types of human dimensions indicators are included in the Aleutian Islands Report Card, which is updated and presented to federal fisheries managers annually (Zador *et al.*, 2017). One human dimension indicator is the annual trend in enrollment in Aleutian village schools, which is considered to be an *in situ* indicator of the sustainability of these rural, ecosystem-dependent communities. The second human dimension indicator is an estimate of the area of seafloor trawled by commercial fishing boats. Much of the commercial fishing is conducted by people who live outside the Aleutian Islands ecosystem. Thus, an estimate of the physical seafloor habitat that commercial fishing boats may encounter is considered to be a measure of direct human impact on the ecosystem, independent of the resident human population. These types of indicators provide fisheries managers with information on the social and economic status of fishing community participants and on ecosystem integrity, both of which inform ecosystem-based fishery management (Zador *et al.*, 2017).

Our overarching goal was to integrate environmental, ecological and human dimensions information important for fisheries into a common analytical framework to examine the linkages between these traditionally separate subjects. We aimed to synthesize across a broad array of data types, representing disciplines such as oceanography, ecology, sociology, anthropology, and economics that are commonly investigated separately. Recent developments in qualitative network modelling (QNM) techniques have enabled relatively rapid and simple analyses across disparate data types that has great potential for integrating human dimensions into fisheries management (Dambacher *et al.*, 2009; Reum *et al.*, 2015; Harvey *et al.*, 2016; DePiper *et al.*, 2017). We used the Gulf of Alaska, United States, as a case study for using QNM to integrate ecosystem and fisheries data, focusing on communities of practice (fisheries sectors) and three common groundfish species to illustrate different kinds of social–ecological interactions in fisheries. Walleye pollock (*Gadus chalcogrammus*, hereafter pollock) are pelagic foraging groundfish that are the subject of a large and economically valuable commercial trawl fishery. Arrowtooth flounder (*Atherestes stomias*, hereafter arrowtooth) are flatfish that function as high level predators in the ecosystem, but commonly have parasitic infections that excrete an enzyme after capture that renders their flesh soft and undesirable for human consumption (Greene and Babbitt, 1990). Thus, there is only a limited targeted fishery for arrowtooth, which is largely used to create ancillary products including fish meal. Although arrowtooth constitute the largest groundfish biomass in the Gulf of Alaska ecosystem, catches averaged only 13% of its allowable biological catch from 2000 to 2014 (Spies *et al.*, 2015). Pacific halibut (*Hippoglossus stenolepsis*, hereafter halibut) are large flatfish that also function as high level predators in the ecosystem. They are the subject of large commercial and recreational fisheries as well as a subsistence fishery for personal use by Alaska residents. There are strict limits on halibut caught in other target fisheries, referred to as Prohibited Species Catch (PSC), which cannot be sold and can influence the execution of other fisheries in the ecosystem.

We focused on synthesis of linkages between the Gulf of Alaska marine ecosystem and communities of practice as defined by fisheries sectors for the three groundfish species. Our specific objective was to document the individual linkages among environmental, ecological, and human dimensions variables in conceptual models, and then build QNMs to perform simulation analyses to test how bottom-up and top-down perturbations may propagate through these linkages. The relative strengths of individual linkages were not documented in the conceptual models, but were randomly assigned during the stochastic simulations to test the effects of the perturbations. We expected to see differences between models of focal species with high and low commercial, recreational, and cultural value. We also contrasted separate models on each focal species with one that merged them through their predation and competition links. We surmised that the separate models would better represent current fisheries management practices, and the merged model would better represent ecosystem modelling efforts.

Methods

Our methods followed a three-pronged approach. We (i) constructed conceptual models for each species and developed a combined model, (ii) implemented these models in QNMs, and (ii) conducted simulations with the QNMs to explore linkages among environmental, ecological, and human dimensions components.

Conceptual models

We constructed conceptual models for each focal groundfish species (pollock, arrowtooth, and halibut) during 4 in-person meetings as members of a National Centre for Ecological Analysis and Synthesis (www.nceas.ucsb.edu) working group from January 2015 to September 2016. We focused on individual models to reflect the current management approach. To develop the models, we synthesized existing scientific knowledge, allowing us to identify key components within and linkages among environmental, ecological, and human dimensions. Environmental variables included climate indices and oceanographic properties such as the Pacific Decadal Oscillation (PDO) and water temperature. Ecological variables were divided into prey (i.e. lower trophic level species), focal groundfish species, and predators and competitors. Human dimensions variables were categorized into aspects of relevant communities of practice (see Supplementary Tables S1–S5 for details on the variables used).

Directionality, and in some cases qualitative magnitude, were recorded for each link. A minimum of one peer-reviewed publication was considered sufficient to support an environmental or ecological link. Although we recognize that our scientific literature review, while extensive, was likely incomplete for any particular linkage, we focused our review efforts on documenting as many links as possible. Links related to prey, predators, and competitors were also informed by a previously published food web model developed for the Gulf of Alaska (Aydin *et al.*, 2007; Gaichas *et al.*, 2010, 2011). To keep the models tractable, only prey that composed $\geq$20% of the focal species diet were included. Conversely only sources of mortality that comprised $\geq$20% were included. These criteria resulted in some linkages with only one direction of influence. For example, euphausiids met the inclusion criteria for prey components of pollock and arrowtooth, but the mortality on euphausiids from either pollock or arrowtooth was not sufficient to include a top-down link. For the human dimensions variables without peer-reviewed studies, directional linkages were based on economic theory, fisheries-dependent data, expert knowledge of the fisheries and markets (Expert knowledge was provided by the authors as well as members of the US National Marine Fisheries Service, Alaska Fisheries Science Centre's Economic and Social Sciences Research Programme.), and the Economic Stock Assessment and Fishery Evaluation Report (Fissel *et al.*, 2016). We visualized the conceptual models using Mental Modeler (Gray *et al.*, 2013; www.mentalmodeler.org).

Qualitative network model

We used the completed conceptual models to build QNMs for each focal species. We then created a combined model by merging the single-species models through predator-prey interactions of the focal species. We chose QNMs because they require no quantitative data and are thus well-suited to integrating multiple types of information where data may be limited or incompatible (Dambacher *et al.*, 2009; Reum *et al.*, 2015). When based on a conceptual model of the social–ecological system (Heemskerk *et al.*, 2003; Dambacher *et al.*, 2009; Orians *et al.*, 2012; Levin *et al.*, 2016), QNMs can provide basic insights into the potential response of the system to different management strategies (DePiper *et al.*, 2017). QNMs are formalized conceptual models that require only a qualitative understanding of how variables interact. Linkages can be categorized as positive, negative, uncertain, or zero values (Dambacher *et al.*, 2009; Reum *et al.*, 2015), and are therefore well-suited to multiple kinds of data limited systems.

We conducted analyses in Qpress, a stochastic QNM software package implemented in the R language (Melbourne-Thomas *et al.*, 2012; R Development Core Team, 2015). Qpress allows for inputs of linkage directionality, but not the magnitude or strength of the relationship. The software constructs a community matrix to represent the system of interest (in our case the linked social–ecological system), with each cell of the community matrix representing the links between nodes as signed directed graphs (either positive, negative, uncertain, or zero values). Self-limitation (a negative self-effect) was included for each node automatically by Qpress. Uncertain linkages can be included in the model, but may represent different types of uncertainty. For example, some uncertain links represent lack of documentation, whereas others represent uncertainty about the direction of the response.

Model simulations

We used the QNMs to perform simulation analyses, implemented in Qpress. We tested two common influences on systems, bottom-up and top-down perturbations (described below), and how each might impact the linkages among environmental, ecological, and human dimensions. To do this, single or multiple variables (nodes) can be "perturbed" to evaluate the impacts of perturbations throughout the model. In each simulation, all system links (community matrix cells) are assigned a random link strength value from [0,1], retaining the input positive or negative sign, to create a new community matrix with random link strengths. Only stable matrices (eigenvalues all negative) are retained for further analysis. A user-specified number of stable matrices (here 1000) are then perturbed as described below, and the impact of the perturbation (positive or negative) is assessed for each variable (node) across the set of stable matrices.

We built the QNMs for each focal species separately, then merged them into one model (hereafter referred to as the merged model) based on all linkages among common variables with each focal species' models. We simulated examples of bottom-up and top-down perturbations on the models to test the effects of these perturbations on the integrated system of the model variables. To assess bottom-up perturbations, we simulated a shift in the PDO index, a climate driver that was included in each model and is related to a well-documented ecological regime shift that occurred in the Gulf of Alaska in 1976/1977 (Anderson and Piatt, 1999), and a shift in phytoplankton, a lower trophic level biological perturbation. To assess a top-down perturbation, we simulated a change in the halibut PSC cap in the groundfish trawl fisheries, which incidentally catch halibut along with targeted groundfish. The halibut PSC cap limits the total amount of incidental halibut catch in the groundfish fisheries, and if this limit is reached, the groundfish fishery is shut down for remainder of the season. Early seasonal closures of groundfish trawl and longline fisheries occur frequently due to reaching the seasonal PSC limit, often resulting in tens of millions of dollars of foregone groundfish revenues (NPFMC, 2013).

When implementing the perturbations in the QNM, we focused on the links where we could specify direction with certainty, but also ran simulations including the uncertain links to assess their effects. For each perturbation, variables for which $\geq$700 of the 1000 simulations that were either positive or negative were considered to have a clear directional response to the perturbation (as per Melbourne-Thomas *et al.*, 2012; Reum *et al.*, 2015; Raymond *et al.*, 2011). Those with $\geq$ 700 zero responses were considered to be unresponsive to the perturbation. Those with both positive and negative responses, but for which neither category with $\geq$ 700, were considered to have equivocal responses. We evaluated the simulations by examining the effects of the perturbations on linkages among environmental, ecological, and human dimensions. We compared the results from single species models to the results from the merged model for each perturbation. We also briefly examined the effects of including uncertain links.

Results

Conceptual models

The conceptual models for each of the three species were similar in structure and complexity among the environmental and ecological components. There were six to seven climate and ocean drivers and four to eight lower trophic and prey components per model (Supplementary Figures S1 and S2; Figure 1). The pollock model included two life stages for the focal species, adult, and juvenile. The arrowtooth and halibut models included a larval stage as well, but the lack of documentation for the link between larvae and juveniles rendered this linkage unaffected by the bottom-up and top-down simulations.

The conceptual models differed in the structure and complexity of the human dimensions, reflecting the nuances of the communities of practice involved in each focal species' fishery. The pollock and arrowtooth models represented single communities of practice, with a relatively simple, single-species target fisheries, and contained eight variables reflecting landings, the total allowable catch (TAC), employment, and profits. The pollock and arrowtooth models also had two and one variables reflecting policy impacts, respectively. In contrast, the halibut model reflected the complexity of a species with four different communities of practice: the targeted commercial fishery (nine variables), as PSC in other groundfish trawl fisheries (eight variables), the recreational fishery (seven variables), and in the subsistence fishery (four variables).

Merging the three focal species models increased the links among common diet items and overlapping predator mortality, but did not greatly expand the number of variables (Figure 2). Notably, halibut and arrowtooth prey on pollock, but pollock prey is predominantly planktivorous, thus, the trophic levels of pollock is lower than that of halibut or arrowtooth. There were fewer shared variables within the communities of practice which increased the total number of variables but not necessarily the link complexity.

Model simulations

We included a relatively small number of linkages with uncertain direction in conceptual models for each species (Supplementary Figures S1; Figures 1 and 2). We compared perturbation results in models with and without these uncertain linkages, and found that in general including uncertain linkages increased uncertainty in outcomes. The results below focus on the models where linkage direction could be clearly specified as positive or negative using the criteria outlined earlier.

Bottom-up perturbations

The simulation of a positive shift in the PDO, associated with increased water temperature, had differing results for the single species vs. merged models (Supplementary Tables S6–S9). In all of the single species models, it led to declines in the pelagic food web variables supporting the focal species, and thus also to declines in the focal species.

The PDO simulation had varying effects on communities of practice, depending on the species and the model. Pollock communities of practice variables such as the number of vessels, crew days at sea, landings, and revenue decreased because pollock abundance decreased. The arrowtooth model had little directional impact on the communities of practice because the target fishery is currently not limited by arrowtooth abundance. In the halibut model, the perturbation led to declines in recreational and subsistence halibut fisheries variables such as profit, catch, and number of trips because halibut abundance declined. However, the directed commercial fisheries variables such as vessels, landings, and price showed equivocal responses due to complexity in quota ownership and management. No effects were seen on other

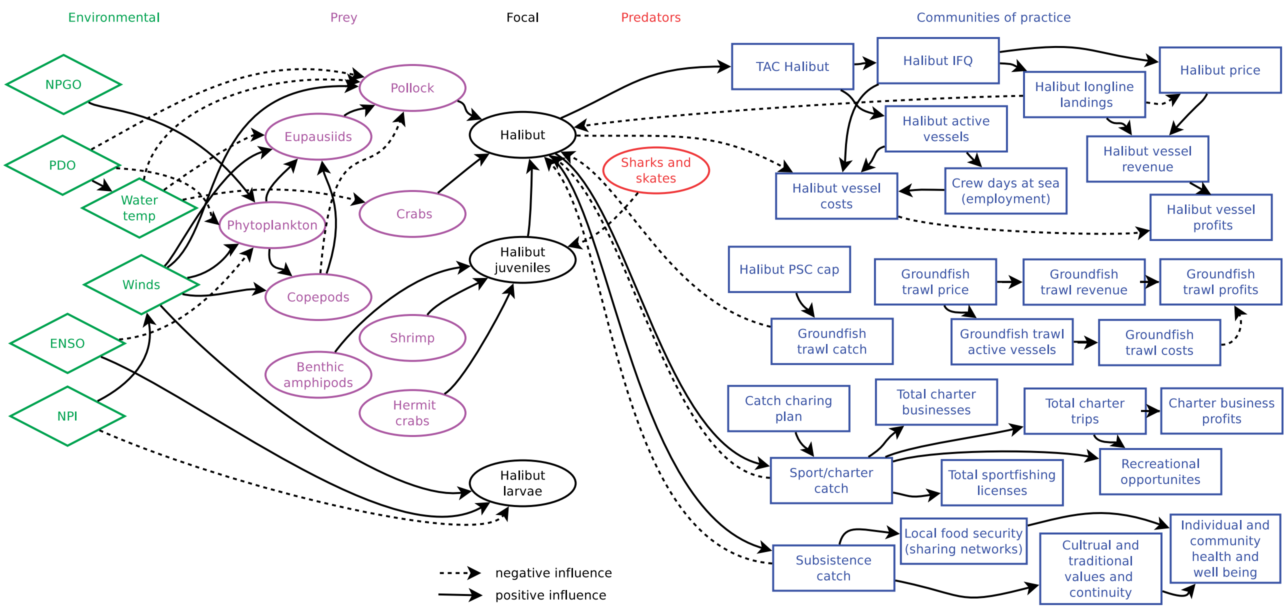

Figure 1. The halibut model. Positive directional links are solid arrows. Negative directional links are dotted arrows.

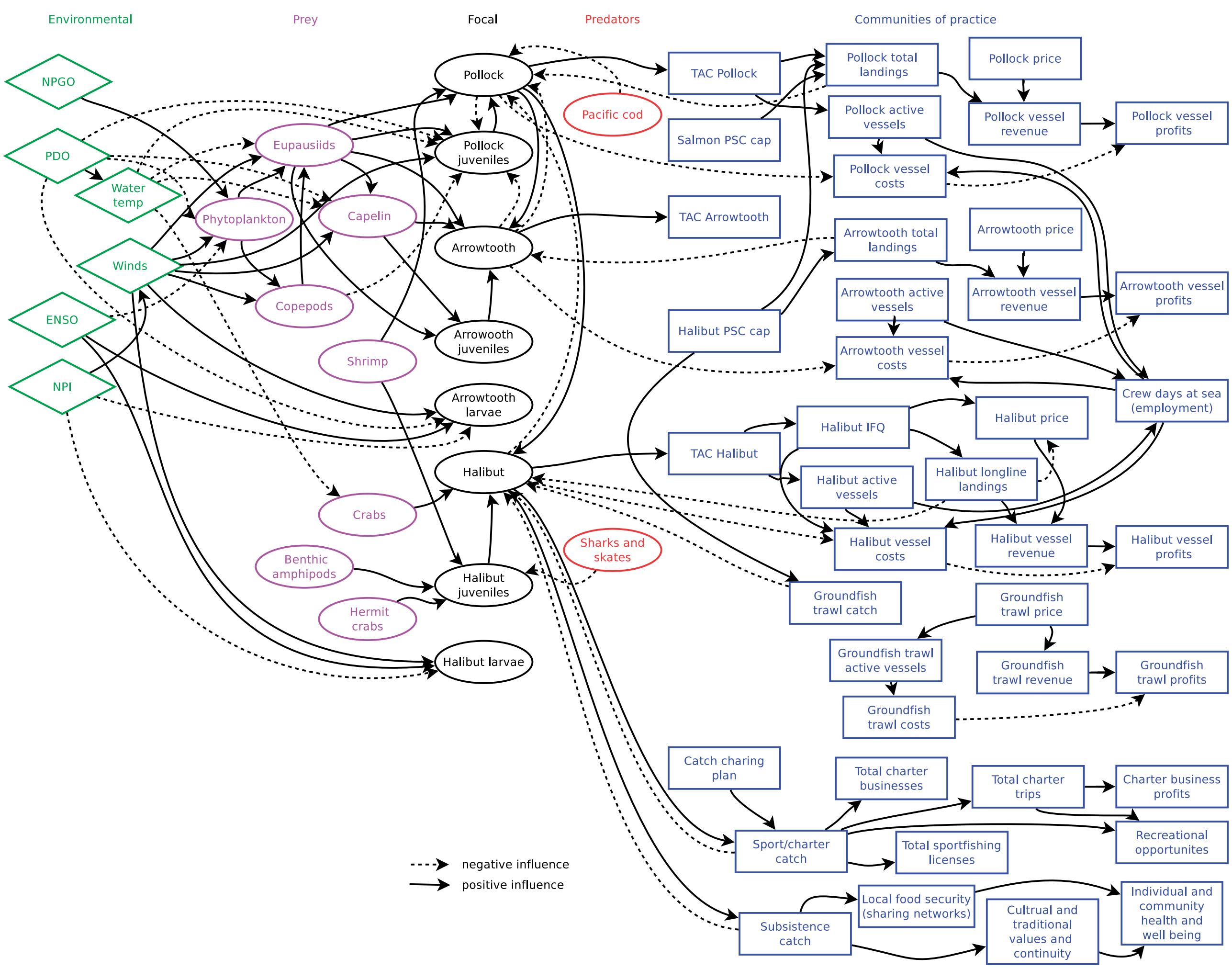

Figure 2. The merged model with pollock, arrowtooth and halibut. Positive directional links are solid arrows. Negative directional links are dotted arrows.

groundfish fisheries in the halibut model because the amount of halibut PSC is currently not related to halibut abundance.

In the merged model, species interactions reversed the direction of response to the PDO increase for both pollock and halibut. Declines in the pelagic food web led to a decline in arrowtooth abundance, which reduced arrowtooth predatory impact on pollock, resulting in an increase in pollock abundance. Because halibut are positively influenced by increases in their pollock prey (and other prey that were not affected by the PDO perturbation), halibut abundance increased. Incorporating multispecies interactions led to increases in halibut abundance (rather than decreases as in the halibut model), which in turn positively affected halibut communities of practice variables such as landings, individual fisheries quotas, community health and wellbeing, and local food security.

When an increase in phytoplankton was simulated, all components of the pelagic food web increased in the focal species and merged models, but effects on communities of practice varied. In the arrowtooth single species model, all components of the food web connected to arrowtooth increased, but the directionality did not propagate through to the communities of practice because they are not connected to abundance of minimally targeted arrowtooth. For the pollock and halibut single species models, the focal species showed equivocal results due to the interplay of top-down and bottom-up effects, and those equivocal results carried through to the communities of practice. In the merged model, both pollock and halibut showed negative responses because arrowtooth increased, mirrored by declines in most variables of the pollock and halibut communities of practice.

Top-down perturbations

Decreasing the halibut PSC cap simulated a policy intervention whereby fewer halibut were allowed to be incidentally caught in (other) fisheries, thus constraining the catch in arrowtooth and pollock communities of practice. No linkages below the focal species in the food web were impacted by this perturbation. In the single species models, the reduction of PSC had a negative impact on the arrowtooth and pollock communities of practice variables such as landings and revenue because they are increasingly constrained by the PSC limit. Assuming that the rate of halibut catch in other fisheries remains the same and the PSC cap decreases, then halibut catch in the groundfish fisheries will decline due to the increasing constraint, which is the intended effect of the PSC cap. However, a decrease in pollock and arrowtooth catch leads to an increase in biomass of pollock and arrowtooth, which then leads to an increase in TAC. This may lead to the counterintuitive result of more vessels and employment in pollock because the qualitative model is not fully linked to account for the constraints on the ability of pollock vessels to catch the entire TAC. This result does not occur in the arrowtooth model because increases in the arrowtooth TAC do not lead to increases in arrowtooth vessels or employment since the arrowtooth fishery is not TAC-constrained. This type of top-down management action is designed to increase halibut abundance, and in the halibut model, this goal is achieved. The halibut communities of practice variables follow accordingly, reflecting the increase in halibut abundance. Only the "other groundfish" community shows declines reflecting the constraining nature described earlier.

When species interactions were accounted for in the merged model, there was an increase in halibut, again as intended by the PSC cap. There was also an increase in arrowtooth abundance, but pollock abundance declined because of the increased negative impact from arrowtooth (and halibut) preying on pollock. This translated through the communities of practice, with a positive influence on all halibut communities of practice variables, but a negative influence for the arrowtooth and pollock communities of practice variables. Notably, pollock TAC decreased due to the decrease in pollock abundance, which eliminates the counter intuitive results from the pollock single species model described earlier.

Discussion

Multiple key insights arise from our work integrating environmental, ecological, and human dimensions information important for fisheries into a common analytical framework. First, the conceptual models allowed us to synthesize information across a broad array of data types, representing disciplines such as ecology and economics that are more commonly investigated separately, often with distinct methods. Second, the qualitative network analysis based on the conceptual models demonstrated how ecological signals can propagate to human communities, as well as how fishery management measures may influence the system depending on the focal species and community of practice. Third, incorporating multi-species interactions can change outcomes; merging the conceptual models to consider qualitative impacts of perturbations on the combined multispecies system reversed some of the ecological and human outcomes relative to single species analyses. Overall, these results demonstrate the value of analyses linking natural and social science knowledge to better understand complex social–ecological systems.

Conceptual models to guide data synthesis

Building conceptual models, which serve as the basis for the QNMs, was a useful process that allowed us to synthesize and analyse varying types of information across disciples in a common framework. For the environmental and ecological data, peer-reviewed literature provided support for documenting linkages. As less information exists about variables relating to the communities of practice, we expanded our sources of support, using a broad array of data types including economic theory, fisheries dependent data, expert knowledge, and fisheries management documents to build the QNMs. This synthesis of data from different sources is one strength of this type of modelling (DePiper *et al.*, 2017), but is not yet common in the literature (but see Ban *et al.*, 2014; Leslie *et al.*, 2015).

The complexity of the conceptual models we built largely reflected the complexity of the fisheries. Many of the environmental variables represented broad-scale processes common to the shared environment of the focal species, and hence were included in multiple single species models. Similarly, there was enough overlap in many of the common diet items among the focal species that the single species models had many of the same variables. However, because the communities of practice were in most cases tied to individual species and fisheries, these variables were more specific to each focal species model, reflecting the diversity (or lack thereof) in their associated communities of practice. These non-overlapping variables then dramatically increased the number of total fisheries-related variables in the merged model, while maintaining the link pathways. This highlights an important advantage using communities of practice in this analysis rather than communities of place. The challenge with communities of place is that each community fishes for many species that may or may not have substantial environmental and ecological linkages, making models much more complex. However, for fisheries managers that aim to fully include human dimensions in management, actions designed with communities of practice in mind will also need to balance factors specific to communities of place if the resident communities of practice are not evenly distributed geographically.

The exercise of assembling information from diverse sources and documenting linkages between variables to construct the conceptual models resulted in two key products: a visual map of the social–ecological systems of interest, and an input dataset for QNM. Both products are useful tools for understanding linkages between previously disparate parts of the systems. The visual map is useful as a communication tool to provide common understanding of system structure, while QNMs can provide insight into basic system behaviour in response to perturbation. Converting visual conceptual models directly into QNMs ensures consistency between tools, and the linkage documentation (Supplementary Material S1) ensures transparency and repeatability of methods. These are desirable qualities for multidisciplinary science where communication and transparency need to bridge gaps between historically separate fields.

Insights from model perturbations

Perturbing the QNMs led to insights into both the behaviour of ecological and human dimensions subsystems, and in particular the differences between communities of practice. Overall, the complex, multi-sectoral halibut fisheries have more endogenous and competing influences that led to less cohesive responses to perturbations. In contrast, the low-value arrowtooth flounder fishery showed fewer confounding influences and more unidirectional response to bottom-up and top-down perturbations. Fisheries variables do not respond to perturbations affecting arrowtooth biology because landings are not connected to arrowtooth abundance.

We observed substantial and consistent changes in the direction of response to perturbations in communities of practice when single-species models were merged into a multi-species model. For all bottom-up and top-down perturbations, changes in response sign among communities of practice (relative to single-species models) consistently propagated from changes in focal species responses due to trophic interaction among the focal species. The negative influence of arrowtooth on pollock represents predation as demonstrated in quantitative food web models, where the biomass-dominant arrowtooth exert high predation mortality on pollock in the Gulf of Alaska (Gaichas *et al.*, 2010, 2015) and in Prince William Sound (Okey and Pauly, 1999; Okey, 2004). When perturbations created positive responses in the lower trophic components of the pelagic food web, arrowtooth increased, which caused pollock to decrease, which in turn caused halibut (predators of pollock) to decrease. The inverse was true when perturbations created negative responses in the pelagic lower food web. Furthermore, the ecological results from our merged qualitative model are consistent with perturbation results from a quantitative food web model of the Gulf of Alaska that incorporates parameter uncertainty, but not linkages to communities of practice (Gaichas *et al.*, 2015). In particular, increases in arrowtooth in the Gulf of Alaska led to clear decreases in pollock and increased phytoplankton production led to clear increases in arrowtooth, but ambiguous directional responses in both pollock and halibut due to the interplay of top-down and bottom-up effects spanning the range of parameter uncertainty (Gaichas *et al.*, 2015).

In the qualitative results presented here, the cascading changes among arrowtooth, pollock, and halibut in turn cascaded to their attendant communities of practice following the same patterns as the single-species models, but with changes in accordance with the sign of focal species change. Additionally, we observed some cases where incorporation of (strong) trophic interactions may increase certainty in perturbation response. For the increased phytoplankton perturbation, there was more certainty in direction of pollock and halibut response in the merged model relative to the single-species models because of greater certainty in arrowtooth response. This increase in certainty may have been due to adding food web interactions *per se*, or to the fact that the key interaction that was added (i.e. arrowtooth, pollock) was a strong interaction. Collectively, these results underscore the benefit of including ecosystem-level processes, even in a single-species fisheries management process. Considering single species models linking variables from environmental to human dimensions makes use of well-developed single species focused data collection and management systems, and has yielded important insights into potential flows of perturbations though our system here. However, our work and that of others demonstrates the importance of considering food web and other interactions in fisheries management to help predict and avoid unanticipated outcomes or side-effects of decisions (Link *et al.*, 2012; Plagányi *et al.*, 2014; Smith *et al.*, 2015; Thorpe *et al.*, 2015).

Conclusions

We found that the relatively novel approach of investigating fully linked social–ecological systems with conceptual models and QNMs shows considerable promise for gaining insight into the behaviour of these systems. Our experience in applying the approach suggests further refinements and considerations for moving forward with these methods. Obviously, the simplicity of conceptual and qualitative models facilitates the use of a wide range of information and knowledges, but limits the types of conclusions that can be drawn from analyses. For example, while the focal groundfish species share the same general habitat of the Gulf of Alaska, our models did not include explicit habitat variables and thus we could not ascertain effects of habitat changes on the focal species or communities of practice. Therefore, rather than testing causality among individual linkages, we focused on the general emerging properties resulting from perturbations propagating through linkages among variables. Further, we built the models for each focal species individually, following our documentation process. Thus, we ended up with some inconsistencies between models (e.g. no pollock larvae group in the pollock model, whereas arrowtooth and halibut larvae groups were represented in their respective models). A lack of documented linkages in turn may limit simulation analysis; unstudied (or unpublished) relationships may be important to the overall system, but cannot be included as linkages using our methods. Similarly, interpretation of linkages may change between contexts, such as between single species and merged multispecies models. For example, we built in an “other groundfish trawl” community of practice in the halibut model to represent those communities that are influenced by halibut PSC restrictions, but are not themselves modelled.

However, when the models were merged, the groundfish community of practice overlapped with the more narrowly defined pollock and arrowtooth communities of practice, yet still left out ecological linkages for other unmodelled but important groundfish.

In addition to ensuring that assembly procedures do not impose unintended limitations on the conceptual model linkages, general methods for QNMs can be explored further. Our qualitative models did not include information on the relative strengths of linkages (which Qpress explored stochastically). If information is available on the strength of links, other methods (including those built into Mental Modeler; Gray *et al.*, 2013) can use it more readily. Linkages with uncertain direction (e.g. between Transport and Juvenile pollock in the pollock model) can also be incorporated into these qualitative models. Although it was not our focus here, we briefly compared perturbation results in models with and without uncertain linkages, and found that in general including uncertain linkages increased uncertainty in outcomes, as might be expected. Because including too many links with uncertain direction may result in a large number of equivocal system responses, a clear and consistent rationale for including (or excluding) uncertain linkages in QNMs would be useful moving forward. Similarly, some software defaults may require evaluation. Qpress automatically adds self-limitation to all nodes, which may not be appropriate for variables such as the PDO. Behaviour of models with selective self-limitation based on the properties of the node should be investigated more thoroughly.

Our integrated approach brought environmental, ecological, and human dimensions information important for fisheries into a common analytical framework that was straight-forward to develop and implement. Although there are very complex ecosystem modelling projects that encompass the environmental, biological, and socio-economic fields, the project we undertook was much simpler and could be performed relatively easily for managers or policy makers tackling broad fisheries management issues. Our approach reflected some of the complexities of marine social–ecological systems, integrating information from disciplines such as oceanography, ecology and economics that are difficult to integrate. Development of conceptual models is an effective way of exploring and synthesizing the current extent of knowledge about a system (e.g. Harvey *et al.*, 2016). Importantly, we showed that perturbations in the system can flow from ecological to human systems, and that results from single vs. merged models provide different insights. Although our models were not intended to be comprehensive, additional complexity could readily be added if desired and appropriate. We believe our work is an early step towards understanding how to incorporate human dimensions into ecosystem-based management. Specifically we demonstrated which variables of the ones in our model were responsive to changes in the ecological part of the systems, and how responsiveness (i.e. directional response) may vary depending on the nature of the fishery and representative variables. We recommend building conceptual models and QNM analysis as efficient early steps to explore ecosystem-based fishery management concerns that can then be followed with more directed and complex analyses. We focused on communities of practice, but the approach is as relevant, but perhaps more complex, for communities of place. We demonstrated the value of analyses linking information from natural and social sciences to better understand complex social–ecological systems, and the value of incorporating ecosystem-level processes into traditionally single species management frameworks.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the article.

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