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Original Article

Examining the expansion of qualitative network models towards integrating multifaceted human dimensions

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Qualitative network models (QNMs) have become a popular tool to assess how ecosystems respond to a perturbation within ecosystem-based fisheries management strategies. Yet, the incorporation of humans into these models is often rudimentary, potentially limiting the accuracy and reliability of the model results. We developed QNMs focusing solely on the social components, derived from content analysis of the literature on the effects of the US Pacific halibut Individual Fishing Quota (IFQ) Program and evaluated how the QNMs performed with respect to simulating the programmatic effects on individual well-being components. The QNMs were effective at reproducing IFQ programmatic effects and demonstrating how well-being heterogeneity across user groups can be incorporated into network models. However, key mechanistic variables were omitted to maintain model stability, reducing our ability to fully replicate the IFQ system. We conclude that QNMs require improvement to incorporate human dimensions that reflect broader social realities. Yet, given the current structural limitations of these modelling frameworks coupled with the complexity of human decision making, there are likely to be continued issues with integrating humans accurately and representatively into these models.

Keywords: ecosystem based fishery management, human dimensions, individual fishing quotas, qualitative network models, well-being

Introduction

There is a growing movement around the world to holistically examine marine ecosystems, integrating diverse ecological elements, scientific disciplines, and knowledge systems into more representative ecosystem models (Link and Browman, 2014; Long *et al.*, 2015). Within fisheries, this has been driven by a response to the flaws in single-species management and the continued transition to ecosystem-based fisheries management (EBFM) (Marasco *et al.*, 2007).

Scientists are increasingly employing conceptual models, operationalized through qualitative network models (QNMs), to facilitate the transition to EBFM and ecosystem-based management more broadly (Dambacher *et al.*, 2015; Harvey *et al.*, 2016; Zador *et al.*, 2017). QNMs were developed as a tool to examine how ecosystems respond to perturbations in data-limited systems (Puccia and Levins, 1985; Melbourne-Thomas *et al.*, 2012). These models are thought to be useful for representing diverse systems, especially in interdisciplinary contexts where the types of knowledge that are included may not be readily examined using quantitative models due to differences in, for example, data availability, units of analysis, and methodologies (Metcalf *et al.*, 2014).

Despite the progress that has been made with QNMs, the incorporation of humans within these models has often been antagonistic and cursory, ignoring the wealth of values people derive from fisheries and how diversified that is across populations. Humans make decisions on the basis of a multitude of factors reflecting their well-being priorities that are not directly comparable to the predator-prey type relationships that form the basis of QNMs well-being is conceptualized as a state of being when needs are met and individuals and communities can pursue their goals and enjoy a good quality of life; it is understood to be composed of numerous components including, for example, livelihood, identity, sense of community, stewardship, social justice and equity, and physical safety (Breslow *et al.*, 2016). To the extent that human well-being is taken into account at all in QNMs, it is generally strictly with respect to the economic welfare components—livelihood and income security (Dambacher *et al.*, 2015; Harvey *et al.*, 2016; Zador *et al.*, 2017).

This approach disregards the holistic understanding of human well-being derived from fisheries participation that has been documented by researchers, including physical and mental health, social relations, a connection to the environment, culture and aesthetics (Breslow *et al.*, 2016). This work builds on extensive efforts by scientists to document the complexity of human interactions with, and derivation of well-being from, their ecosystems more broadly moving from basic needs to security, health, social relations, and freedom (MEA, 2005), as well as seminal work on valuing well-being and the equity dimensions of that (Dasgupta, 2001). The distribution of well-being components is generally incorporated into QNMs under an assumption of homogeneity across populations, despite research indicating that well-being is in fact highly individualized due to differences in access, values, needs, and priorities (Coulthard, 2012; Coulthard and Britton, 2015).

Within QNMs, this prevalent disregard of the complex nature of the human well-being components derived from fisheries can have adverse implications in terms of the accuracy and applicability of the model results. Applying only an economic understanding can produce inaccurate results given that multiple other facets of well-being will also have implications for participants' decision making (Hall-Arber *et al.*, 2009; Lord, 2011). For example, fishermen often have a deeply ingrained fishing identity that sometimes results in them remaining in fisheries even in the face of severe revenue declines (Pollnac and Poggie, 2006; Holland *et al.*, 2019). Omitting the human diversity in how well-being is derived from fisheries can exacerbate underlying inequities and lead to management choices that increase social conflict and decrease resilience (Hall-Arber *et al.*, 2009; Carothers *et al.*, 2010; Lord, 2011).

In various contexts, network models have been developed to incorporate human dimensions using a mix of participatory processes, expert knowledge, and established theory (DePiper *et al.*, 2017; Zador *et al.*, 2017; Pittman et al., 2020). Although a participatory process has the benefit of knowledge exchange between stakeholders and researchers, it can be resource intensive and limiting in terms of the applicability of the results to other communities (Rosellon-Druker *et al.*, 2019; Szymkowiak and Kasperski, 2020). This may in part account for the limited incorporation of human dimensions into QNMs, focusing on economic welfare components, which can be readily derived from economic theory. Yet in some contexts, a wealth of literature exists documenting linkages in socioecological systems that can be conceptualized as human dimensions elements for incorporation into a QNM. Using such resources to build the human dimensions of QNMs is an analogue to how ecological systems are often developed in these models, relying on literature and researcher expertise for interpretation.

In this paper, we use content analysis of the literature about the impacts of the US Pacific halibut Individual Fishing Quota (hereinafter IFQ Program) as a case study to derive a diversity of well-being outcomes associated with the program and the heterogeneity of those across fisheries participants. This literature includes multiple ethnographic studies which examine the impacts of a fisheries program from the perspective of stakeholders. The method presented in this paper therefore advances the representative incorporation of human dimensions into QNMs by using the rich literature that exists for the Pacific halibut IFQ program to incorporate model elements that are stakeholder-derived without the capital and time investment necessary to conduct primary research. We broaden the scope of human dimensions that are included within QNMs by developing models that integrate a diversity of well-being components tied to IFQ objectives. We further focus specifically on IFQ leasing in the program to explore the heterogeneous nature of well-being on diverse stakeholder groups.

Pacific halibut IFQ Program

The IFQ Program was implemented in 1995 for the directed commercial halibut fishery off Alaska in response to overcapacity and overfishing (NPFMC/NMFS, 2016). Under the program, qualifying participants received quota shares (QS), a privilege to harvest a guaranteed percentage of the total allowable catch (TAC), based on their fishing history. The IFQ Programmatic objectives were intended to mitigate adverse effects on communities and crewmembers, maintain fleet diversity, prevent excessive consolidation, and ensure fishery benefits flowed to active participants. It was anticipated that the guaranteed harvesting privilege associated with QS would eliminate the incentives for derby-style fishing, prolong the fishing season, and provide fishing flexibility that would, in turn, allow for numerous other benefits including greater physical safety, increased product quality, decreased gear loss and associated issues with bycatch, discards, and undocumented fishing mortality.

The IFQ Program was chosen as an appropriate case study due to its diversity of participants and programmatic objectives, the coupling of which provide an opportunity to examine well-being across users and multiple components. Furthermore, given the longevity of the program (25 years), there is a wealth of literature on its various effects, which allows for documenting numerous variables and linkages specific to human dimensions. The multifaceted objectives of the program can be translated into a diversity of well-being components that in turn can be evaluated using QNMs Programmatic effects specific to IFQ leasing can be explored as heterogeneous well-being outcomes across distinct user groups, given substantial increases in leasing practices since the program implementation, multiple efforts by managers to curtail the practice, and several studies specifically exploring these dynamics.

Data and methods

The following sections describe the stepwise methodology, which we applied to examine multiple well-being components and heterogeneity in well-being distribution across distinct user groups. The sections detail how we conducted a systematic literature review, employed content analysis for developing conceptual models, developed conceptual models specific to IFQ implementation and leasing, and utilized QNMs to examine IFQ effects.

Literature review

The variables and linkages in the QNMs are derived from a systematic analysis of the literature specific to the IFQ Program, which was used to build the underlying conceptual models. The 20-year comprehensive review of the program served as the basis for the literature review (NPFMC/NMFS, 2016), and all of the literature cited within the 20-year review was incorporated into our analysis. Publications that in turn cited the literature within the 20-year re-

Table 1. Human well-being components, their definitions, and example phrases. The components and definitions were derived from the literature on human well-being associated with marine ecosystem uses and fisheries (Coulthard, 2012; Amberson *et al.*, 2016; Breslow *et al.*, 2016; Biedenweg *et al.*, 2017; Szymkowiak and Kasperski, 2020). The phrases are example quotes within the IFQ Program literature that link to each of the components.

Human well-being component	Definition	Example phrases from the IFQ Program literature
Identity	Sense of self and community identity	"Being a fisherman," "fishing careers"
Sense of place	Meaning and identity connected to a place	"Place attachments," "place-based"
Sense of community	Social relationships within community	"Social conflict," "fishing relations"
Family connection	Intra-family relationships	"Bring their children on board"
Education and Information	Possession and transmission of knowledge, information, and skills	"Knowledge of the marine environment"
Personal development	Building human capital	"Lack of exposure, experience," "professional"
Cultural values and traditions	Transfer of customs, practices, values	"Customary share system," "norms, values"
Stewardship	Sustainable practices and conservation	"Bycatch and waste," "fishing mortality"
Family heritage	Generational connections to uses	"Family connections to fishing," "inherit"
Self-determination	Independence and agency	"Ability to choose," "bargaining position"
Social justice	Equitable distribution of benefits from the resource	"Access issues," "inequities"
Income security	Evidence of stability and ability to plan into the future	"Variation in annual revenues," "financial risk"
Livelihood	Employment and income	"Jobs," "employment"
Physical safety	Protection from exposure to threats	"Vessel loss," "fishing fatalities"
Resilience	Social-ecological adaptability	"Adjusting to fluctuations," "stability for rural fishing livelihoods"
Sustainability	Long-term, multi-generational practices	"Maintaining remote villages," "sustainability of the fishery system"

view were also explored for content specific to the IFQ Program. Additional literature was identified using the peer-reviewed literature databases Google Scholar and Scopus, to search permutations of the following terms: IFQ Alaska, halibut, privatization, management, and quota. A total of 26 peer-reviewed publications were thus identified, 14 of which employ ethnographic research techniques including interviews, focus groups, and surveys that examine programmatic outcomes from diverse stakeholder perspectives including the 20-year review itself. Coupled with the 20-year review, these publications were analysed as described below (see Supplementary Table S1 for publications identified).

Development of conceptual models

The conceptual models of IFQ effects were derived from the literature identified in the literature review described above. The literature was analysed to determine the specific text that discussed effects of the IFQ program. The text was then coded using content analysis, wherein each phrase was dissected to determine the variables being discussed and the linkages between them (Wrightson, 1976). For example, "the cascading enclosure and commodification of fishing rights is severing the place, resource, and livelihood attachments of Kodiak communities" (Carothers, 2010) was used to determine negative links from altered succession ("cascading enclosure and commodification of fishing rights") to sense of place ("place attachments"), to stewardship ("resource attachments"), and to livelihood ("livelihood attachments") (Supplementary Table S1 presents in detail how variables and linkages were determined from the literature). The well-being components in the conceptual models were derived from the congruence of the language within the IFQ Program literature to definitions of well-being components for the connections between humans, marine ecosystem uses, and fisheries that are in the literature (Coulthard, 2012; Amberson *et al.*, 2016; Breslow *et al.*, 2016; Biedenweg *et al.*, 2017; Szymkowiak and Kasperski, 2020) (Table 1). Through this process of content analysis, well-being components and their associations with the variables of interest in the models were determined.

Because relationships between variables have been given varying degrees of attention within the literature, linkages only had to appear once in the content analysis for them to be included in the models (e.g. fresh production and impacts on communities with and without transportation), accounting for about half of the linkages in the models. Basic microeconomic theory was applied for linkages between costs, revenues, and profits, QS prices and lease fees, wherein such relationships could not be derived from the literature. Two linkages for which the literature indicated contrasting results, i.e. findings that implied different directional relationships, were not included in the model. This included the impacts of crew bargaining power on altered succession and of season length on fisheries diversification. For crew bargaining power on altered succession, the contrasting results lay within the complex relationships emerging over the course of the IFQ Program between limited crew jobs concurrent with fewer crew available and the acquisition of QS as a potential bargaining tool for crewmembers. Additionally, the differentiated strategies of specialization and diversification emerging with the prolonged fishing season implied different directional relationships with season length on fisheries diversification.

A number of simplifications were made to the models to facilitate stability and interpretability. The well-being components were demarcated as the terminal variables in the model, eliminating relationships between the well-being components themselves as well as between well-being components and other variables in the model.

Conceptual models of IFQ implementation and leasing

We used QNMs to simulate IFQ effects on multiple stakeholder groups and across multiple well-being components. In order to examine the applicability of QNMs in modelling diverse human dimensions, we developed five distinct conceptual models that were divided between two categories. The first category was developed to simulate the effects of IFQ implementation on programmatic objectives as they relate to well-being. It included three conceptual models that serve as proxies for different well-being components—(i) gear loss and stewardship, (ii) physical safety, and (iii) fishing communities. Although within the "communities" model the community variables are the terminal variables, it is understood that those variables, in turn, represent a number of different well-being dynamics that have been associated with IFQ programmatic objectives for fishing communities and the effects of the IFQ program on those communities. Most prominently and perhaps as distinct from effects at the individual level explored in the other models are social justice and equity issues associated with the displacement of small operations (Carothers *et al.*, 2010; Carothers and Chambers, 2012; Ringer *et al.*, 2018; Coleman *et al.*, 2019). In order to provide for model stability, we included only the links that were pertinent to the final variable(s) of interest (i.e. gear loss and stewardship, physical safety, and communities).

The second category of models was developed to simulate the effects of IFQ leasing on the heterogeneity of well-being effects across two distinct user groups—crewmembers and QS holders. These models include all of the well-being components documented in the literature as associated with leasing impacts on crewmembers and QS holders as well as all of the variables and linkages that provided for those well-being outcomes. The well-being components are also the terminal variables in the crewmembers and QS holder models of leasing and include cultural values and traditions, education and information, family connection, family heritage, identity, income security, livelihood, personal development, physical safety, resilience, self-determination, sense of community, sense of place, social justice and equity, and stewardship.

Programmatic models

The conceptual models that examine well-being effects tied to programmatic objectives were specific to (i) gear loss and stewardship, (ii) physical safety, and (iii) communities. The three models presented with a conceptual framework (Figure 1) and matrix (Figure 2), respectively, were developed to encapsulate a number of distinct objectives. The first of these—gear loss and stewardship ("gear loss")—examines a number of specific problems that the programmatic objectives were intended to address, including gear conflicts, deadloss from lost gear, bycatch loss, and discard mortality, all of which are associated with lost gear and are not in line with stewardship practices. By extending the fishing season and increasing fishing flexibility, the IFQ Program was anticipated to allow the halibut fleet to spread out fishing operations over time and space and thus limit congestion on fishing grounds. Coupled with consolidation and the associated reduction in the number of participants in this fishery, the program was anticipated to reduce gear conflicts and associated issues.

Similarly to gear conflicts, physical safety in the fishing fleet was one of the programmatic objectives aimed to address with the implementation of the IFQ Program. It was anticipated that the benefits provided by increased fishing flexibility and a prolonged fishing season would increase safety in the fishery. In addition to being a programmatic objective, safety is a component of well-being, and the variables and linkages for this component are encompassed in the "safety" model.

The IFQ Program includes a number of objectives regarding access and equity for fishing communities into the IFQ fisheries that are associated with a variety of other well-being components including, for example, personal development, livelihood, income security, identity, and family heritage. Indeed the loss of access into these fisheries following IFQ implementation and associated rising entry costs have been associated with (among others) social conflict, loss of family connection as well as cultural values and traditions, and disconnect from sense of place, community, and knowledge of the water (Carothers, 2008, 2010; Ringer *et al.*, 2018; Coleman *et al.*, 2019). The communities model categorized fishing communities based on four characteristics to reflect the NPFMC's communities of interest for IFQ effects as well as characteristics specified within the literature. The following four variables were included in the communities model: (i) rural communities, (ii) communities with transportation, (iii) communities without transportation, and (iv) indigenous communities (Carothers *et al.*, 2010; Carothers and Chambers, 2012; NPFMC/NMFS, 2016; Szymkowiak *et al.*, 2019; Szymkowiak *et al.*, 2020). Rural communities are primarily defined as those with populations of fewer than 2500, communities with transportation are those with access to the road system or an airport, and indigenous communities are those comprised of individuals that identify as Alaska Natives and the Alutiiq communities of the Kodiak archipelago examined in specific studies (see NPFMC/NMFS, 2016 for additional details on community characteristic definitions) (Carothers, 2010, 2013). With the exception of communities with and without transportation, these four categories are not mutually exclusive, so that linkages within the model may span multiple community variables.

Concerns regarding IFQ effects on rural communities were associated with the potential for a redistribution of fishing privileges away from those communities, similar to what was observed following the implementation of limited entry programs for various State fisheries (NPFMC/NMFS, 2016). The distinction with respect to transportation access reflects concerns that prolonging the fishing season under IFQs would shift processing towards fresh production and result in a reliance on the capacity to move product quickly, necessitating access to transportation. A lack of access to such transportation would impede the capacity of remote processors to compete for landings with others who were targeting the fresh market and could offer higher ex-vessel prices (NPFMC/NMFS, 2016). Indigenous communities may fall under any of these other community categories and have been the subject of targeted research due to disproportionately adverse effects as well as deep cultural and spiritual ties to their local marine resources (Carothers *et al.*, 2010; Carothers and Chambers, 2012).

Leasing models

The remaining two models intended to simulate the effects of IFQ leasing on crew and QS holders, allow for the examination of the heterogeneous well-being distribution across distinct users and their unique well-being outcomes (Figures 3 and 4). The intent of examining IFQ leasing was to evaluate a programmatic provision that had distinct outcomes on heterogeneous groups (NPFMC/NMFS, 2016). The IFQ Program allows initial recipients to use hired masters (anyone designated by the QS holder) to land their IFQ, which is effectively leasing. Despite multiple efforts to try to curtail it, this practice has increased tremendously since IFQ implementation from about 40% of the harvested TAC in 2014 compared to 13% at the start of the program (NPFMC/NMFS, 2016).

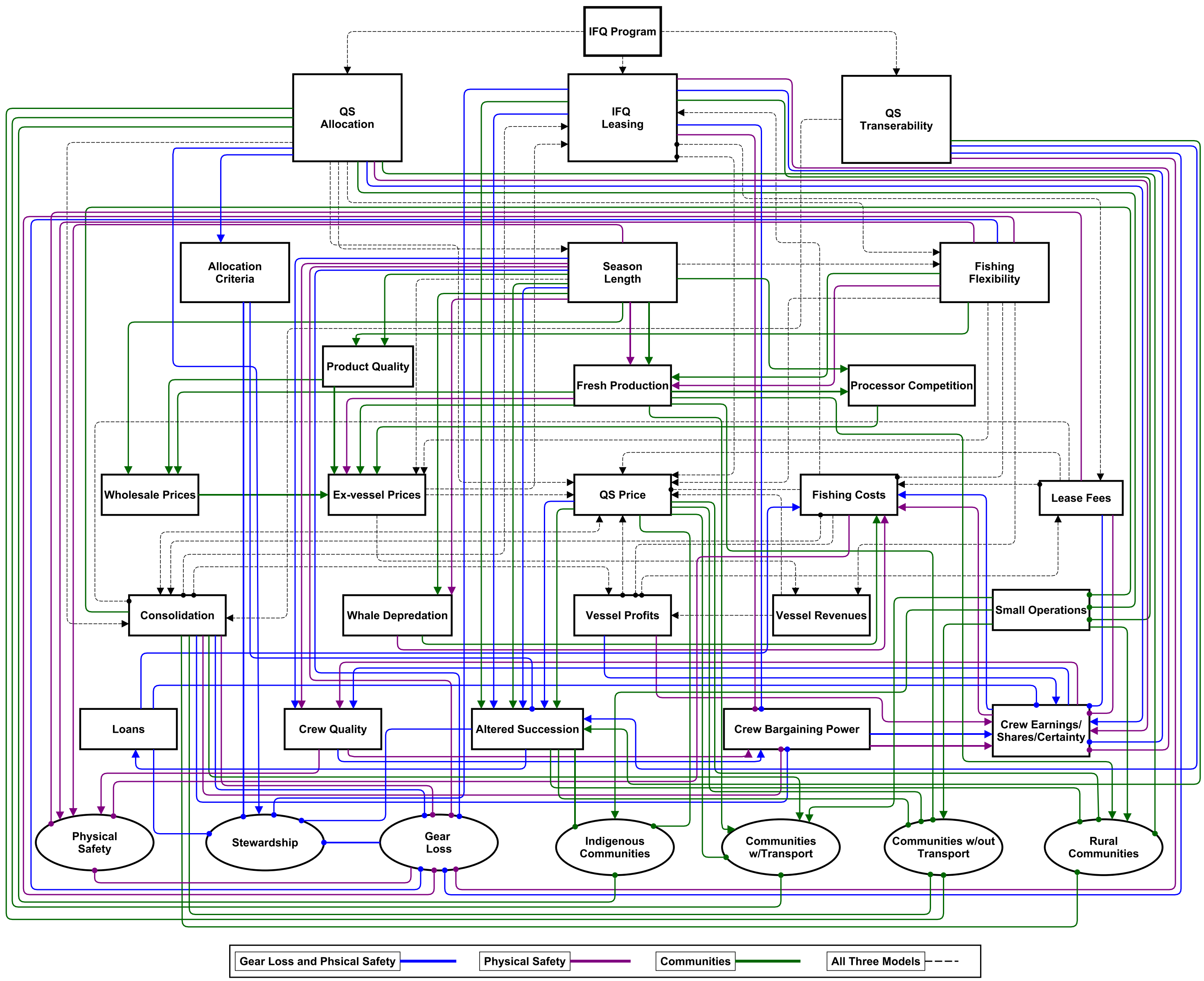

Figure 1. Conceptual model of gear loss, physical safety, and communities. All variables (nodes) have a negative self-interaction (not shown). A line terminated with an arrowhead indicates a positive influence and a line terminated with a dot indicates a negative relationship. Blue lines indicate links specific to gear loss and stewardship model; magenta lines indicate links specific to the physical safety model; green lines indicate links specific to the communities model; dashed lines indicate links shared by all three models. Oval nodes are specific to terminal variables.

Figure 2. Matrix representation of gear loss, physical safety, and communities conceptual models, includes negative self-interactions (not shown). Symbols within squares indicate the link direction (+, −). Figure created with R package "ggplot2" (Wickham, 2016). Blue boxes indicate links specific to the gear loss and stewardship model; green boxes indicate links that are specific to the community model; purple squares indicate links that are specific to the physical safety model; orange squares indicate links that are shared by the gear loss and stewardship and physical safety models; red squares indicate links that are shared by the gear loss and stewardship and community models; teal squares indicate links that are shared by the community and physical safety models; grey squares indicate links that are shared by all three programmatic models. Variables that do not appear on the *x*-axis are terminal within the model.

Because leasing has been the subject of multiple papers specific to the halibut IFQ fishery (Szymkowiak and Himes-Cornell, 2015; Szymkowiak and Felthoven, 2016; Szymkowiak *et al.*, 2020), the QNM results can also be triangulated similarly to the other models.

The crewmembers model examines the effects of leasing with well-being components specific only to crew, while the QS holder model examines effects specific to QS holders. The literature discusses a number of different effects that we parsed into multiple variables, including crew bargaining power, crew jobs, crew quality, and crew earnings/shares/certainty. The last of these was originally included as separate variables, but were ultimately combined into one (hereinafter "crew earnings") due to shared linkages and to aid in model stability. These various crewmember variables have coupled responses that in turn induce effects on well-being variables. The relationships between variables are different for the two models, reflecting divergent incentives for crewmembers and QS holders. In particular, there is a positive relationship between lease fees and leasing for QS holders as rising fees reflect a greater percentage of the revenues going towards QS holders, incentivizing more leasing. However, in the crewmember model, an increase in fees results in less leasing as vessel owners are likely to be disincentivized from leasing when a greater percentage of their revenues goes to QS holders. The crewmember variables and their linkages in the QS holders model are the same as those in the crewmember model, reflecting how effects on those variables are the same even when the well-being of interest is that of QS holders. The QS holder model was built to incorporate both the QS holders operating strictly as lessors and those that continue to actively participate in the fishery but own QS, which could provide many of the same benefits to them as it does to the absentee owners.

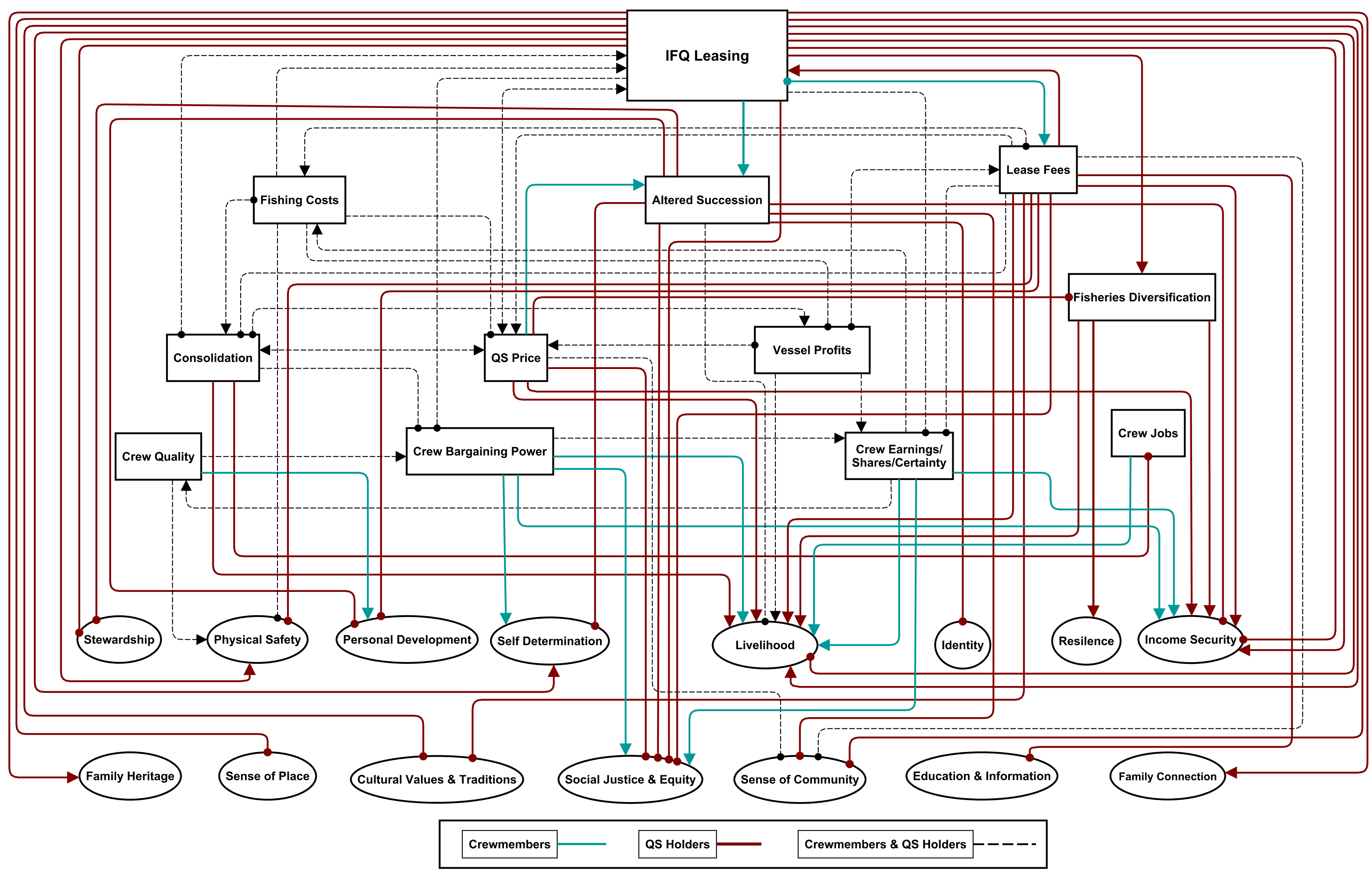

Figure 3. Conceptual model of crewmembers and QS holders. All variables (nodes) have a negative self-interaction (not shown). A line terminated with an arrowhead indicates a positive influence and a line terminated with a dot indicates a negative relationship. Blue lines indicate links specific to the crewmembers model; red lines indicate links specific to the QS holders model; dashed lines indicate links shared by both models. Oval nodes are specific to terminal variables.

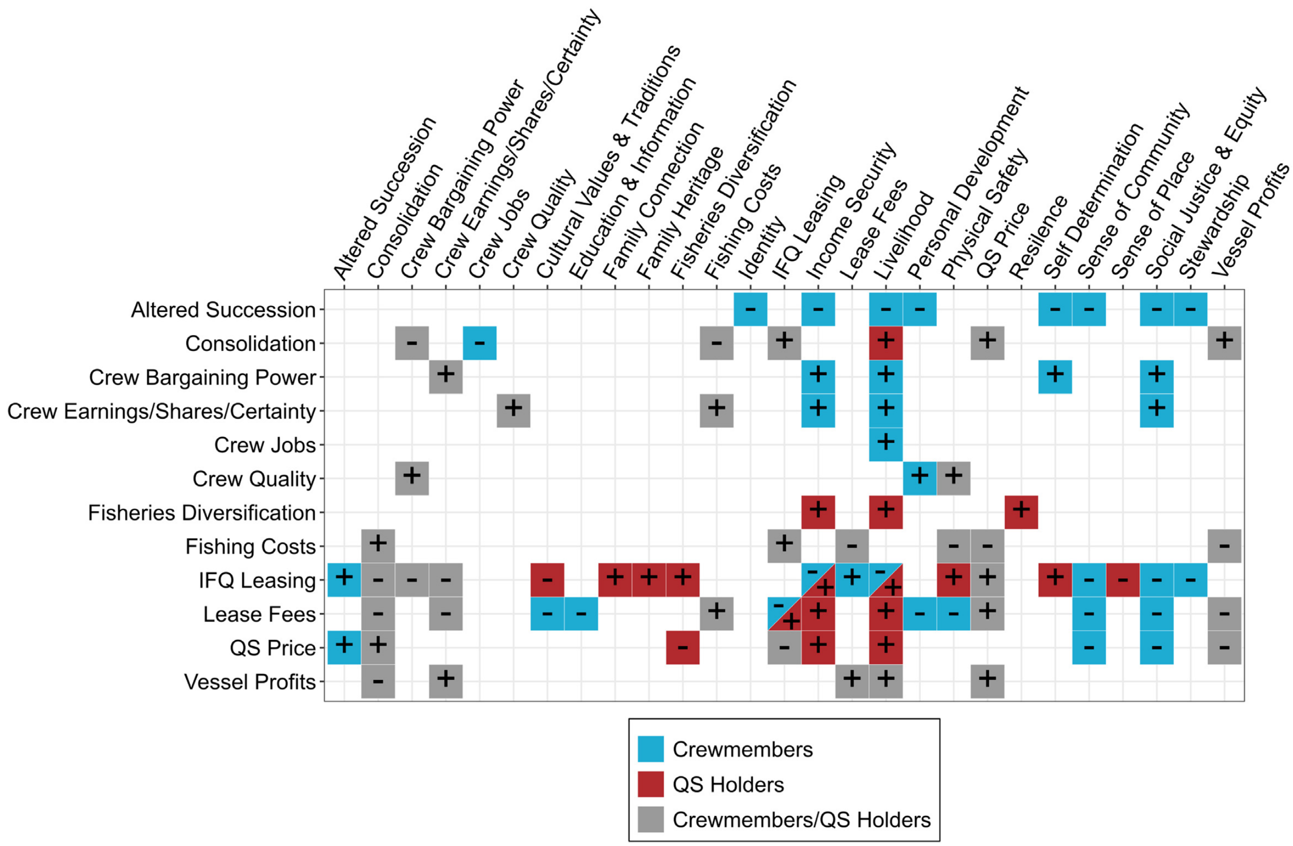

Figure 4. Matrix representation of crewmember and QS holders conceptual models, includes negative self-interactions (not shown). Symbols within squares indicate the link direction (+, −). Figure created with R package "ggplot2" (Wickham, 2016). Blue boxes indicate links specific to the crewmembers model; red boxes indicate links specific to the QS holders model; grey boxes indicate links that are shared by both models. Variables that do not appear on the *x*-axis are terminal within the model.

QNMs and perturbations

QNM analysis was conducted in R (R Core Team, 2019) utilizing the QPress package. The QNM framework uses the link interaction between variables of a system to qualitatively examine the impacts of a press perturbation. A sign directed graph (visualized as a conceptual model) is constructed by assigning variable (node) link interactions as either positive (+), negative (-) or neutral/uncertain (0) (Dambacher *et al.*, 2009; Reum *et al.*, 2015). The QPress package constructs a community matrix from a sign directed graph and allows for users to specify which variables (nodes) to perturb by either increasing (+1) or decreasing (−1) the variable(s) of interest (Melbourne-Thomas *et al.*, 2012). Self-limitation (−1) is incorporated into each variable to account for assumed negative self-effects not included in the model and to enhance overall model stability (Dambacher *et al.*, 2002; Melbourne-Thomas *et al.*, 2012). Random variable interaction strengths are assigned and the resulting simulated community matrix is tested against stability criteria (Melbourne-Thomas *et al.*, 2012). Only the stable matrices are retained and the inverse of these matrices is used to determine the predicted response of a community to a press perturbation. This was repeated on the retained stable matrices 10000 times, from which we summarize the responses of each variable (distribution of positive or negative responses) to the perturbation. A response was considered consistent if it was positive or negative 70% of the time or more (Harvey *et al.*, 2016; Zador *et al.*, 2017).

A press perturbation allows for a preliminary understanding of how a system responds to a new equilibrium evoked by a sustained perturbation in a variable of interest (Bender *et al.*, 1984). For example, a number of studies have examined how biological communities respond to a press perturbation, such as by increasing parameters associated with long-term climatic and environmental conditions spurred by climate change, like increased sea surface temperatures, and the subsequent impacts on species interactions and abundance (Harvey *et al.*, 2016; Marzloff *et al.*, 2016). The five models described above were differentially perturbed, depending on the impacts of interest. The IFQ Program variable was perturbed (+1) to simulate the implementation of the IFQ Program in the models for gear loss, safety, and communities. The IFQ leasing variable was perturbed (+1) to examine the impacts of instituting leasing across heterogeneous user groups for the crewmembers and QS holders models. The impacts of the perturbations are the outcomes of how the change permutates through the pathways that are established within the conceptual model.

Results

Programmatic models

The results demonstrating the IFQ programmatic effects on gear loss, physical safety, and communities from the QNMs are consistent with realized outcomes, in effect demonstrating that similarly

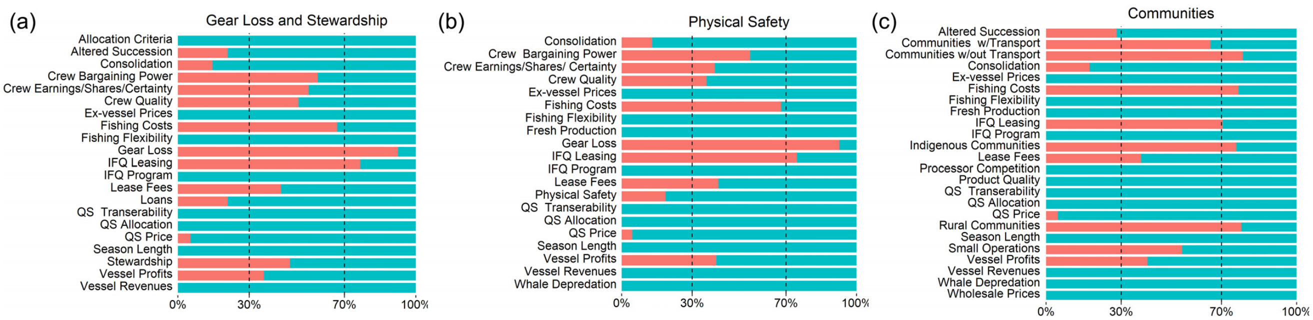

Figure 5. Simulation results to a positive perturbation in the IFQ Program. The 30 and 70% lines represent the cutoffs for which positive and negative results, respectively, can be interpreted from the figures as consistent. Red shading, negative response; green shading, positive response. Note that different variables are included across the three panels because the conceptual models differ slightly across the three objectives of interest. Figure created with R package "ggplot2" (Wickham, 2016).

to biological systems, social systems can be reproduced with QNMs developed based on content analysis of literature (Figure 5a–c). The negative response in gear loss in Figure 5a (93%) implies a reduction in lost and abandoned gear, which is aligned with documented programmatic effects (Knapp, 1997; NPFMC/NMFS, 2016). The results for stewardship are considered equivocal with low sign consistency (47% negative); stewardship is responding to other variables in the model that do not have causal linkages with gear loss and that pull the stewardship variable in opposite directions. There is an assumed inverse relationship between leasing and stewardship due to how lessees' incentives are decoupled from the long-term health of the resource relative to QS holders (Bradshaw, 2004; Gibbs, 2009). Due to the 77% negative response in leasing, stewardship is pulled in a positive direction. The practice of leasing has also been associated with changes to upward mobility in the fishery captured by the positive response of altered succession (80%)—a concept that is intended to encapsulate diminished opportunities for participants to move from crew to vested positions like permit holders and vessel owners and quota shareholders, which has been documented within Alaska (Szymkowiak and Himes-Cornell, 2015; Ringer *et al.*, 2018; Coleman *et al.*, 2019). In turn, altered succession and the resulting reliance on loans (79% positive) pulls stewardship in a negative direction as participants are stressed to make payments and stay afloat in fisheries more broadly while facing squeezed margins (van Putten and Gardner, 2010). Furthermore, allocation criteria (100% positive) associated with the implementation of the program and the distribution of QS to those with fishing history also adversely affected stewardship as fishermen attempted to increase their fishing history in order to receive more harvesting privileges (Carothers and Chambers, 2012).

Physical safety demonstrates a positive response (82%) (Figure 5b) with IFQ implementation, reflecting similar research findings following the first several years of the program (Knapp, 1999 ; Hughes and Woodley, 2007). The main drivers influencing the positive response in safety are the prolongation of the season (100%) and fishing flexibility (100%) that resulted from the IFQ program. Although safety has a consistently positive result, in the underlying model safety is negatively affected by the reduction in crew quality that is driven by higher lease fees. The variables associated with program implementation—IFQ Program, QS allocation, QS transferability—are always going to have consistent results because they were in fact components of the IFQ Program itself. The other variables with universally positive impacts (ex-vessel prices, fresh production, vessel revenues, and whale depredation) have consistent effects driven by how the implementation of the IFQ Program has been documented as having led to an increase in fresh production which provided for higher prices and vessel revenues, while the prolonged season afforded whales a greater opportunity to learn how to depredate on fishing gear, which are explained in more detail below.

The results from the communities model also revealed variation in programmatic effects (Figure 5c). Communities without transportation, rural communities, and indigenous communities have a consistently negative response (78, 77, and 75%, respectively) to IFQ implementation. This reflects negative impacts from a shift in processing needs towards fresh production (100% positive), adverse impacts from QS allocation and altered succession (100 positive and 72% positive, respectively), as well as consolidation (83% positive) and rising QS prices (95% positive). On the other hand, the effects on communities with transportation (67% negative) are considered equivocal. This is aligned with the literature on the IFQ Program, which indicates that even among rural communities those with transportation benefitted from a redistribution of IFQ landings and QS holdings with the shift towards fresh production. Regardless, the QS allocation process and rising QS prices had similarly negative implications for this group of communities as they did for the other categories in this model (NPFMC/NMFS, 2016).

The intent of the programmatic models is really to focus on the variables of interest for each figure, i.e. gear loss and stewardship, physical safety, and communities. However, some of the other variables also have results that can be triangulated. For example, season length has had a demonstrable increase from 24 hours in some cases prior to IFQ implementation to an eight-month season following the program (NPFMC/NMFS, 2016). The positive response in ex-vessel prices (100%, Figure 5a–c) is also aligned with programmatic outcomes associated with a switch to fresh production (100% in Figure 5b and c), as in turn are positive responses in vessel revenues (100%, Figure 5a–c) (Hermann and Criddle, 2006; NPFMC/NMFS, 2016). Similarly, wholesale prices have responded positively (100%, Figure 5c) to changes in processing following IFQs (NPFMC/NMFS, 2016). Consistently positive responses for consolidation and QS prices across the three programmatic models are similarly aligned with known IFQ effects. Following IFQ implementation, the number of vessels participating decreased by 73% while the number of QS holders decreased by 44% from the baseline period of the three years preceding the program to 2014 (NPFMC/NMFS, 2016). Similarly, QS prices increased by 228 to 276% from 1995 to 2014 for the two largest IFQ areas by

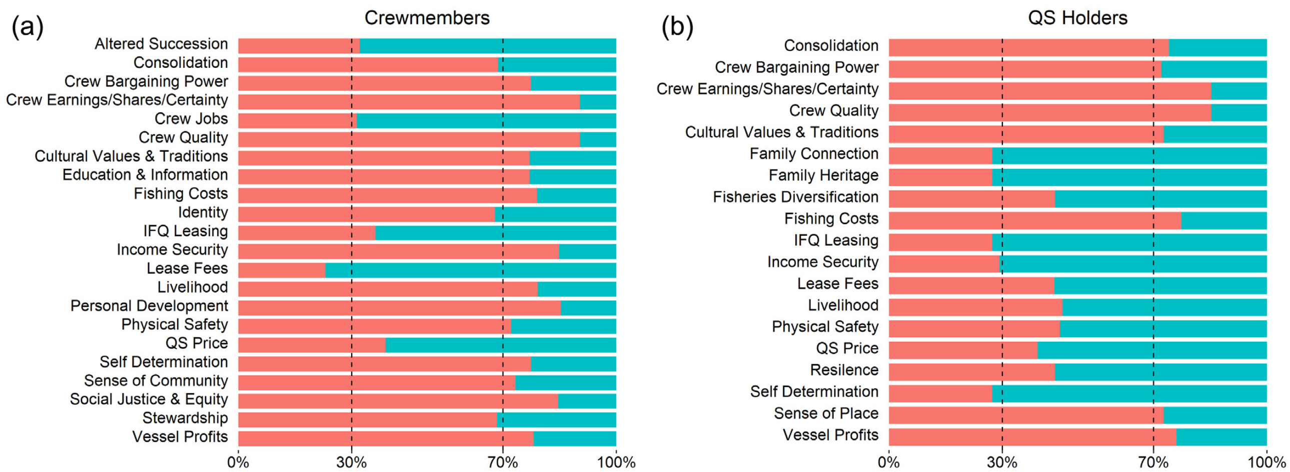

Figure 6. Simulation results to a positive perturbation in IFQ leasing. The 30 and 70% lines represent the cutoffs for which positive and negative results, respectively, can be interpreted from the figures as consistent. Red shading, negative response; green shading, positive response. Note that different variables are included across the two panels because the conceptual models differ slightly in terms of the well-being components that were specified for crewmembers and QS holders in the literature specific to leasing effects.

volume (areas 2C and 3A, respectively) (NPFMC/NMFS, 2016). Whale depredation is only posited to have been affected by season length in the conceptual models, which researchers have associated with increased opportunities for depredation; thus, the positive response within Figure 5b and c is also aligned with expectations (Peterson and Carothers, 2013). Several other variables in the model—allocation criteria, QS allocation, and QS transferability—are essentially just programmatic mechanisms that do not have any other inputs and will therefore always result in positive outcomes.

The only tractable variable that has an effect not aligned with the literature is IFQ leasing, which has a consistently negative response across all three models in Figure 5; whereas, in actuality, the practice increased substantially (NPFMC/NMFS, 2016). In all three models, this response is driven by an inverse relationship with fishing costs, which have a negative response (just under the threshold for consistency in the gear loss and safety models but above it in the communities model). Fishing costs are not tracked in the halibut IFQ fishery, but were expected to decrease in response to efficiency gains from IFQ implementation (NPFMC/NMFS, 2016). Vessel profits, which are also not tracked in this fishery, have a universally equivocal response across the three models due to the push and pull of revenues and costs.

Leasing models

The effects on crewmembers of perturbing IFQ leasing are shown in Figure 6a. The leasing perturbation triggers a positive response in lease fees (76%) and it is the coupling of these two impacts that affects many of the other variables in the model. The compounding effect of IFQ leasing and lease fees is a negative response in sense of community (72%) as well as a reduction in crew bargaining power (77%) and crew earnings (90%). The negative impacts on those two crewmember variables, in turn, trigger a negative response in crew quality (90%), which together reduces crews' personal development (85%) and physical safety (73%). Reductions in crew earnings and crew bargaining power also contribute to negative responses in their livelihood (79%), income security (84%), self-determination (77%), and social justice and equity (84%). Negative responses in cultural values and traditions (76%) and education and information (76%) are associated strictly with the positive response in lease fees. Both the responses in stewardship and crew jobs are equivocal with low sign consistency in the crewmember model. Despite an inconsistent result, we note that contrary to the other crewmember variables in the model, crew jobs respond positively (68%) due to their inverse relationship with consolidation. Because leasing can be a financially beneficial alternative to selling QS for QS holders, the increase in leasing leads to a reduction in QS consolidation relative to the scenario in which leasing is not happening implying that there are more boats on the water and thereby additional crew jobs.

Some results of the crew model are not aligned with programmatic outcomes while others have effects that cannot be triangulated due to a lack of data. For example, QS prices and consolidation both have equivocal responses in Figure 6A although as discussed in the programmatic model results above both have increased demonstrably since IFQ implementation. Despite an effect on fishing costs that mirrors that of the programmatic models (79% negative), vessel profits also have a consistently negative response (77%) due to positive responses in lease fees and QS prices which are inversely related to profits.

Similarly to the crewmembers model, it is the coupling of IFQ leasing and lease fees that triggers many of the responses in the QS holders model (Figure 6b). In contrast to the crewmember model, many of the well-being outcomes in the QS model are positive, reflecting that QS holders as a group may benefit from the increased flexibility afforded by IFQ leasing and associated opportunities to reduce physical and financial risks, pointing to disparities in programmatic outcomes across generational groups despite the NPFMC's efforts to mediate adverse impacts (NPFMC/NMFS, 2016). Although this is reflected in a positive response in income security (71%), livelihood has an equivocal response (54% positive). The latter is driven down by a direct relationship with fisheries diversification (56% positive), which, in turn, is responding negatively to QS prices (61% positive) under the assumption that high prices impede acquisition and portfolio diversification. Inconsistent results for resilience (56% positive) are similarly linked to the potential negative response in fisheries diversification. Although the flexibility of leasing provides QS holders with the opportunity to avoid being out on the water and exposing themselves to risk, for those QS holders still operating vessels the decrease in crew quality (85% negative) flowing from lowered crew shares increases risk. These effects are coupled together to produce an inconsistent response in physical safety (55% positive). Leasing is solely responsible for positive responses in family heritage (72%), family connection (72%), and self-determination (72%) as the capacity to lease allows QS holders to determine how to allocate their time and potentially spend more of it with family. However, even for QS holders, the bifurcation of community members into winners and losers following the institution of the IFQ Program has been exacerbated by leasing, represented by negative responses in a sense of place (72%) and cultural values and traditions (72%).

Similarly to the crewmember model, some responses in the QS holders model are not aligned with programmatic model outcomes. This includes an equivocal response in QS prices and a consistently negative response in consolidation (74%). Contrary to the programmatic models wherein the IFQ Program is the perturbed variable, the perturbation of leasing coupled with its positive effect on lease fees results in a negative response in consolidation as QS holders have an economically beneficial alternative to selling QS. Also similarly to the crewmember model, vessel profits, and fishing costs have consistently negative responses in the QS holders model (77 and 78%, respectively) due to the same relationships as the crewmember model.

Discussion

This study provides a venue for understanding the complexities in meaningfully incorporating a variety of well-being components and diverse user groups into QNMs In general, the QNMs developed for this study were effective at reproducing IFQ programmatic effects across objectives and demonstrating how well-being heterogeneity across user groups can be incorporated into network models. When triangulated with the literature on IFQ effects, the QNM results were aligned with programmatic effects on the objectives of gear loss, physical safety, and communities.

The application of content analysis in this context showcases how this tool has the potential to integrate a more holistic understanding of human dimensions within QNMs In many cases, social dynamics are actually more data limited than ecological systems and most often lack any systematic documentation of variables and their linkages (Olsson and Jerneck, 2018). In our study, the determination of human dimensions variables from the literature allowed for a systematic examination of how individuals have derived well-being from the Pacific halibut IFQ fishery and how that was affected by the IFQ Program. The wealth of literature available on this program and its rich ethnographic content allowed the building of human dimensions components of a QNM that implicitly accounts for stakeholder input and experience of this fishery. In similar contexts, content analysis can be used to document variables and linkages in social systems incorporating human dimensions that are often largely omitted from consideration. This method is especially applicable wherein primary data gathering for building QNMs is constrained by time or capital and literature exists documenting well-being components of interest. Although as others have noted, the spatial scale of these models is an important consideration as key variables and linkages may be different across communities, making extrapolation from the local to regional scale potentially fraught (Harvey *et al.*, 2016), similarly to issues with making assumptions about the consistency of well-being priorities across communities (Biedenweg et al. 2014).

Similarly to diverse well-being components, incorporating heterogeneity across divergent user groups is constrained within QNMs due to homogeneity in link directionality (Harvey *et al.*, 2016). For example, the increasing practice of IFQ leasing and rising lease fees imply a greater % of vessel revenues to the QS holder and decreased earnings for crew. This implies differing relationships between model variables and well-being components for crewmembers and QS holders. Ignoring that variation may mask some potentially adverse effects on specific user groups when QNMs are used to examine the impacts of perturbations. Although as Harvey *et al.* (2016) note, that variation can often occur at the level of individuals, influenced by distinct personal histories, cultural heritage, and beliefs, which makes it inherently prohibitive to capture in a QNM. In this study, we captured the heterogeneity across user groups in IFQ effects by having distinct models for crewmembers and QS holders. Although having distinct models can result in issues of interpretability, alternatives to this approach, such as including separate nodes for well-being components of diverse user groups, e.g. "crew livelihood" and "QS holder livelihood," can destabilize models and preclude the interpretation of results.

Although we were able to examine systemic effects of the IFQ Program on individual well-being components, we were unable to analyse all of the variables initially identified due to resulting issues with model stability. We were thus constrained to developing individual models that examine distinct well-being components, and ultimately we were only able to use 47 of the 101 variables that were initially identified in the literature review. This required omitting variables such as mental health and food security, two components that are inextricably linked to individual well-being, impeding understanding the tradeoffs across multiple well-being components. We also qualitatively aggregated a few variables similarly to previous reductionist approaches that are common in network models due to shared causal and effect linkages between these groups of variables (Harvey *et al.*, 2016; Zador *et al.*, 2017). However, as others have noted, applying reductionism to human dimensions is arguably more problematic than for ecological components due to the inherent complexity and intersectionality of social, political, and economic systems (Crenshaw, 1989; Olsson and Jerneck, 2018). The reduction in scale required to increase stability also reduces our ability to understand the processes specific to mechanistic variables and how possible effects may manifest themselves. This diminishes our capacity to fully replicate the IFQ system and thus the processes underlying some IFQ programmatic effects, which is necessary information for managers to be able to shape policy tools to facilitate intended outcomes.

The tradeoffs in model development and interpretability elucidated herein contribute to a growing body of research highlighting the structural uncertainties surrounding QNMs (Melbourne-Thomas *et al.*, 2012; Harvey *et al.*, 2016; Novak et al., 2016; Wildermuth *et al.*, 2017). Models specific to distinct user groups may be difficult to reconcile but they can also point to potential overall disparities in management impacts while moving away from difficult comparisons of specific well-being outcomes across users (Wildermuth *et al.*, 2017). Furthermore, the assumptions of linearity underlying QNMs implies that these models do not appropriately account for relationships that may in fact fundamentally shift if a perturbation is strong enough (as noted for biological QNMs by Reum *et al.*, 2015), or because they are inherently nonlinear dynamics fundamental to the socioeconomics of fisheries (Gordon, 1953). Other network models, like fuzzy cognitive maps (FCMs) may allow the strengths of relationships to be weighted which can facilitate the incorporation of individualized perceptions of linkage strengths, value systems, and well-being heterogeneity (Ozesmi and Ozesmi, 2004). However, the methods for incorporating uncertainty within FCMs are arguably less developed than for QNMs (Melbourne-Thomas *et al.*, 2012; Baker *et al.*, 2018).

Conclusions

Although QNMs are being increasingly utilized to examine how system perturbations may affect social and ecological variables and the tradeoffs of management choices, the extent to which the human dimensions in these models reflect reality or are meaningful has been limited. In shifting the focus to the social components alone, this study examined the extent to which human dimensions could be effectively integrated and modelled within the QNM framework. Even though we demonstrate that QNMs can be expanded to improve the incorporation of human dimensions by integrating the multifaceted and heterogeneous nature of human well-being, this study also showcases the limitations of these models in doing just that.

The simplistic underpinnings of QNMs are intended to facilitate coupling knowledge systems across disciplines and linking social and ecological components. However, it is arguably this simplicity that hinders the meaningful integration of human dimensions within these models. The heretofore limited focus within QNMs on economic welfare and assumptions of human homogeneity have to some extent hindered the broader utility and versatility of these models in examining the effects of perturbations and management tradeoffs. Given the complexity of how humans make decisions and interact with their marine ecosystems, the outright reductionism of complex relationships that is necessary within QNMs is arguably more limited in its ability to accurately reflect social than ecological dynamics. Researchers then need to consider whether incorporating humans into QNMs given current structural limitations is sufficiently meaningful to warrant the tradeoff with having that integration not be an accurate reflection of social realities.

Supplementary data

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

Data availability statement

The data underlying this article will be shared on a reasonable request to the corresponding author.

Author contributions

MS devised the project and its main conceptual ideas, analysed the data, conducted content analysis, and developed the manuscript. MRR created the figures, assisted in the content analysis, data analysis, and in manuscript development. Both authors contributed to manuscript revision, and read and approved the submitted version.

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