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Original Article

Social-ecological approaches to shellfish aquaculture using qualitative network models

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Integrating social and ecological aspects of bivalve aquaculture in research and management processes can improve understanding of the system as a whole, and facilitate management decision-making. We created social-ecological conceptual models of Pacific oyster (*Crassostrea gigas*), Manila clam (*Venerupis philippinarum*), and Pacific geoduck (*Panopea generosa*) aquaculture in a USA estuary, which were the basis of qualitative network analysis to compare: (i) social-ecological models versus truncated ecological- and social- only models, and (ii) two geoduck models representing different stakeholder groups' perspectives on nature-based recreation and environmental stewardship. The social-ecological models predicted different results compared to individual social or ecological models, including for abundance of invertebrates, eelgrass, and marine water quality. The two alternative geoduck models predicted outcomes that varied across multiple social-ecological variables, including the availability of local harvestable food, sense of place, and abundance of invertebrates in structured habitat. Results demonstrate the interconnectedness of the social and ecological components of the aquaculture system, and how predicted outcomes can vary depending on their inclusion in the model. This study also demonstrates the value in considering a suite of models that represents a range of group perspectives to identify areas of conflict and agreement, and to recognize bias inherent in the models.

Keywords: Aquaculture, *Crassostrea gigas,* clam, geoduck, oyster, *Panopea generosa*, qualitative network model, social-ecological system, *Venerupis philippinarum*.

Introduction

The sustainable development of aquaculture is dependent on interdisciplinary approaches to research and management to provide a more holistic understanding and context for management decisions (Siddiki and Goel, 2017; Mather and Fanning, 2019; Weitzman, 2019). An integrated systems approach that includes both social and ecological dimensions can improve management outcomes by reducing conflict in permitting, and increasing social license and trust in management decisions (Stead, 2019). Bivalve aquaculture, like many other food production systems, has strong connections with the ecological system, cultural values, historic resource use, access rights, and competing interests among industry and stakeholder groups, amongst other issues. However, research has tended to focus on the ecological or social aspects of aquaculture in isolation, which limits the potential to gain insight into how the system as a whole will respond to different aquaculture expansion scenarios or management decisions (Costa-Pierce, 2010; Krause *et al.*, 2015). Further, this single disciplinary approach limits ecosystem approaches to shellfish aquaculture which emphasize identification of tradeoffs, uncertainties, and potential unexpected outcomes associated with management action (Soto, 2007; Link *et al.*, 2010).

While some multi-disciplinary analyses include physical, ecological, or social aspects of aquaculture, few encompass a holistic, integrated approach across the system (e.g., Ferreira *et al.*, 2008; Callaway *et al.*, 2012; Alleway *et al.*, 2019; but see Johnson *et al.*, 2019). Ostrom's social-ecological systems framework (Ostrom, 2009; McGinnis and Ostrom, 2014) provides a framework within which to integrate information across disciplines, levels of complexity, varying types of data collected on different scales, and uneven data availability (Liu *et al.*, 2007; Raymond *et al.*, 2011; Stier *et al.*, 2017). Perceptions regarding the environmental and social implications of aquaculture can also vary widely across aquaculture stakeholders and user groups (D'Anna and Murray, 2015; Froehlich *et al.*, 2017; Mather and Fanning, 2019). All of these challenges complicate efforts to represent the complete aquaculture system. The development of a social-ecological conceptual model can be the first step in advancing ecosystem approaches to aquaculture management

Conceptual models of aquaculture systems can support dialogue on the state of knowledge of various ecological and social components and relationships, and highlight similarities and differences in perceptions and values of different stakeholder groups (Harvey *et al.*, 2016; Levin *et al.*, 2016; Rosellon-Druker *et al.*, 2019). They focus attention on describing the integrated aquaculture system and are not limited to specific disciplinary knowledge domains or narrow sets of relationships where data may be available for more quantita-

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tive approaches. Importantly, conceptual models can also be recast as qualitative network models (QNMs), which provide a formal framework for making qualitative predictions of system responses to different perturbations (Puccia and Levins, 1985; Harvey *et al.*, 2016). Essentially, the conceptual models define the direction, sign (increase, decrease, or neutral) and certainty of links connecting variables, while the QNMs determine the predicted change (sign and certainty) in each variable, integrating across all direct and indirect links in the model, in response to a perturbation. Conceptual models are converted into networks, where only the positive, negative, or neutral effect of one variable on another is specified. With QNMs, feedbacks and indirect effects implied by the network are incorporated into predictions (Puccia and Levins, 1985; Melbourne-Thomas *et al.*, 2012). QNMs are flexible enough to be applied in a range of systems, and have been applied to fisheries management (Metcalf *et al.*, 2014; DePiper *et al.*, 2017; Martone *et al.*, 2017; Zador *et al.*, 2017), conservation (Sobocinski *et al.*, 2018; Reum *et al.*, 2019), and climate change (Harvey *et al.*, 2016). QNMs have also been used to characterize shellfish aquaculture, but only with respect to ecological aspects of the system (Reum *et al.*, 2015a; Reum *et al.*, 2015b).

Bivalve aquaculture in Puget Sound, Washington (USA) is an ideal case study to examine the social-ecological system through conceptual models and QNMs. The $118 million Washington State, bivalve, aquaculture industry (USDA National Agricultural Statistics Service, 2017) is expanding in the region, and includes the cultivation of Pacific oysters (*Crassostrea gigas*), Manila clams (*Venerupis philippinarum*), and the Pacific geoduck (*Panopea generosa*) in the inter-tidal zone of Puget Sound. Commercial shellfish aquaculture has existed in Washington State for over a century and was predated by tribal subsistence harvest of wild shellfish and cultivation via clam gardens (Lepofsky *et al.*, 2015). Despite the history of shellfish cultivation in the USA West Coast region, development of the industry has caused concern among some groups due to the potential for adverse environmental impacts, changes to coastal landscapes, and reduced access to shore-based recreation, among other issues (D'Anna and Murray, 2015; Hudson, 2016; Ryan *et al.*, 2017). Others see the potential benefit to the economies and identities of rural communities, improved environmental stewardship, and the broader benefit of providing sustainable, local food (D'Anna and Murray, 2015; Hudson, 2016; Ryan *et al.*, 2017). Two common methods of growing oysters in this region include directly on the intertidal sediment ('on-bottom') and suspended above the sediment in mesh bags or on longlines ('off-bottom'). Clams are grown on gravelly sediment under anti-predation nets. The longer-lived geoducks are initially grown in polyvinyl chloride (PVC) tubes (10–15 cm diameter), covered in netting, and inserted into the tideflat. These anti-predation tubes are removed after approximately two years and the geoducks are harvested after a total of five to seven years. Geoduck culture is particularly controversial in the region, with stakeholders holding divergent perspectives on its ecological (e.g., PVC tubes adding pollution and altering habitat) and social impacts (e.g., impacting beach access) (Rudell, 2012; Ryan *et al.*, 2017). In addition to varying public perceptions, the industry also occurs in an environment of complex regulations and limited data to inform management (Hudson, 2016; Ryan *et al.*, 2017). Disciplinary studies have been conducted to help fill ecological and social knowledge gaps in the region, but no research on the integrated social-ecological system has been conducted (Dumbauld *et al.*, 2009; Northern Economics Inc., 2010; McDonald *et al.*, 2015; Ferriss *et al.*, 2016; Ryan *et al.*, 2017).

QNMs remain a relatively new approach to representing indirect effects and feedbacks in aquaculture, but from a research perspective, they are well-suited to exploring the potential consequences of resolving social components. In this study, we identified how integrating different types of information in aquaculture models can influence predicted outcomes of expanding aquaculture, applied to Puget Sound, Washington (USA) as a case study. First, we developed social-ecological conceptual models of four types of aquaculture: Pacific oysters grown directly on the sediment (on-bottom), Pacific oysters grown suspended above the sediment (off-bottom), Manila clams, and Pacific geoduck aquaculture. Second, we evaluated the implications of using a social-ecological model, versus a model that has only social or ecological variables, to evaluate implications of expanding aquaculture on other components of the system, using QNMs. Last, we examined how the incorporation of different perspectives into the social-ecological conceptual model structure affected predicted outcomes of expanding aquaculture on the other variables. Understanding the potential implications and challenges of incorporating multidisciplinary data and multiple perspectives into aquaculture research can help develop an informed basis for predicting the consequences of management decisions on social-ecological systems. This case study also explores the use of QNMs as a tool to advance the research and conversation around aquaculture expansion.

Methods

We developed 13 conceptual models centered on the major types of intertidal shellfish aquaculture in Puget Sound, WA: Manila clams, Pacific oyster on-bottom (grown directly on the sediment), Pacific oyster off-bottom (grown in suspended mesh bags or on longlines), and geoduck (Figure 1). Three conceptual models were developed for each type of aquaculture: two models that included only ecological or social components of the system, and a third social-ecological model that coupled the two separate social and ecological models. We developed separate social and ecological models for each type of aquaculture, to focus attention on their unique ecological and social context and to simplify identification of key sources of uncertainty in the model predictions. For the purposes of this study, we used the term 'social' to include variables related to social and economic variables (as per Ostrom, 2009, but omitting political variables). We created an additional, 'alternative' social-ecological conceptual model for geoduck aquaculture that differed structurally and reflected different stakeholder perspectives on its social impacts. Geoduck was selected as a case study within this suite of models to explore the potential influence of considering multiple perspectives in the analysis, given the availability of published literature accounting for some of these diverging views. These 13 conceptual models were then converted to qualitative network models to predict changes in the variables based on an increase of the cultured shellfish represented in that model. Predicted changes in variables were compared across models within a type of aquaculture and between types of aquaculture to identify how these alternative ways of portraying a system can influence

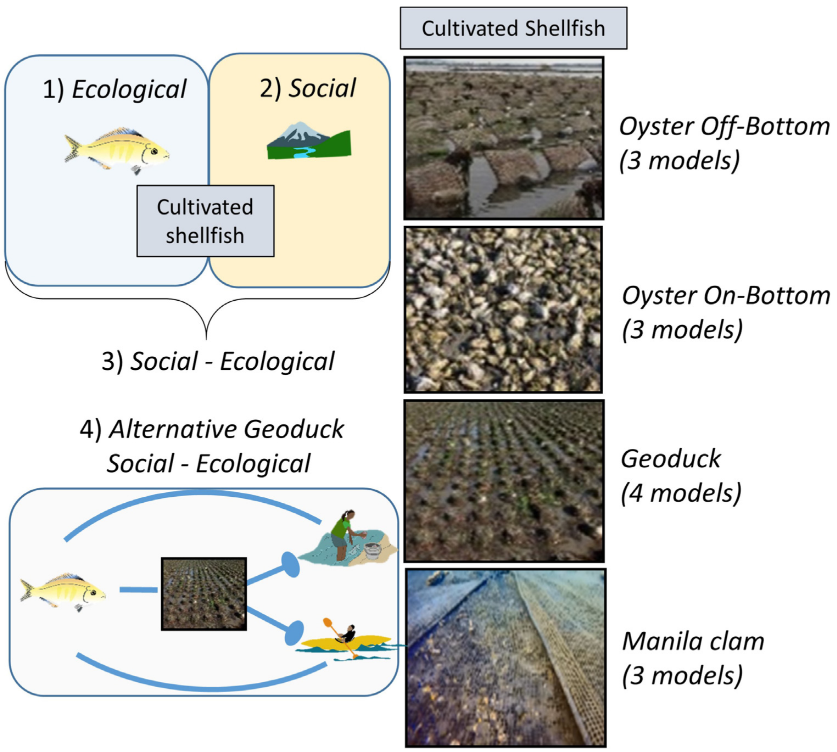

Figure 1. An overview of the 13 conceptual models created for geoduck (four models), Pacific oyster onbottom (three models), Pacific oyster off-bottom (three models), and Manila clam (three models) aquaculture. Each type of aquaculture had three conceptual models (social-ecological, social, and ecological), with an additional model created to represent alternative perspectives on geoduck aquaculture (a negative impact on Nature-based Recreation and Stewardship). The conceptual models were then converted to qualitative network models (QNMs) to predict changes in variables based on increased aquaculture.

predicted outcomes of increased aquaculture. We provide a brief overview of the ecological, social, and social-ecological conceptual models below, with additional details of the models and their linkages in Figure 2 and the supplemental information (Supp. Table 1, Supp. Figs 1–3).

Conceptual Model Development

Model Variables

The ecological components of the models were based on a previously published Puget Sound bivalve aquaculture model (Reum *et al.*, 2015b). Our four ecological models include six species/functional groups and two habitat variables, including: species of commercial, recreational, and cultural importance (e.g., salmon and crab), functional groups consisting of multiple species as defined by their ecological role or association with different habitat types (e.g., small fish and structure-oriented invertebrates), and eelgrass (*Zostera marina*). Eelgrass is included due to its habitat value for fish and invertebrate species in intertidal areas, spatial overlap with shellfish aquaculture, and importance in siting permits (i.e., aquaculture operations are frequently excluded or limited in areas where eelgrass occurs). The links in the ecological part of the model represent predator-prey relationships between the species/functional groups and their connection to eelgrass as habitat.

We selected variables from the Puget Sound Partnership's list of Puget Sound Vital Signs to populate the social conceptual models (https://vitalsigns.pugetsoundinfo.wa.gov/, accessed August 15, 2020; Table 1), consistent with other social science research and indicator development on the Puget Sound marine system (e.g., Biedenweg *et al.*, 2014; Biedenweg *et al.*, 2016; Biedenweg *et al.*, 2017; but note exceptions outlined in the Discussion section below; Table 1). The Puget Sound Partnership is a Washington State Agency (USA) tasked with leading conservation and recovery efforts in Puget Sound. This suite of indicators has been in development since 2010 and is intended to provide a holistic representation of the health of Puget Sound and progress towards its recovery goals, including: water quality, water abundance, habitats, species and food webs, healthy human populations, and vibrant human quality of life. We selected social indicators that were relevant to shellfish aquaculture: *Local Harvestable Foods* (e.g., subsistence and recreational fishing and shell fishing), *Nature-based Recreation* (e.g., participation in kayaking, walking on beach), *Economic Vitality* (including employment in natural resource industries, natural resource industry output, percent of total Gross Domestic Product in natural resource-based industries), *Sense of Place* (extent to which people identify with and feel positively attached to a specific place), *Stewardship* (caring for the marine environment), *Salmon Catch* (*Oncorhynchus* spp.), and *Crab Catch*. We also included *Marine Water Quality* (i.e., levels of pollution) as it has direct relevance to permitting of areas for shellfish harvest for human consumption. We altered definitions of some of these indicators from those provided by the Puget Sound Partnership to better address the aquaculture context (Local Harvestable Foods), or did not update the definitions for those that were changed by the organization since the study began (Marine

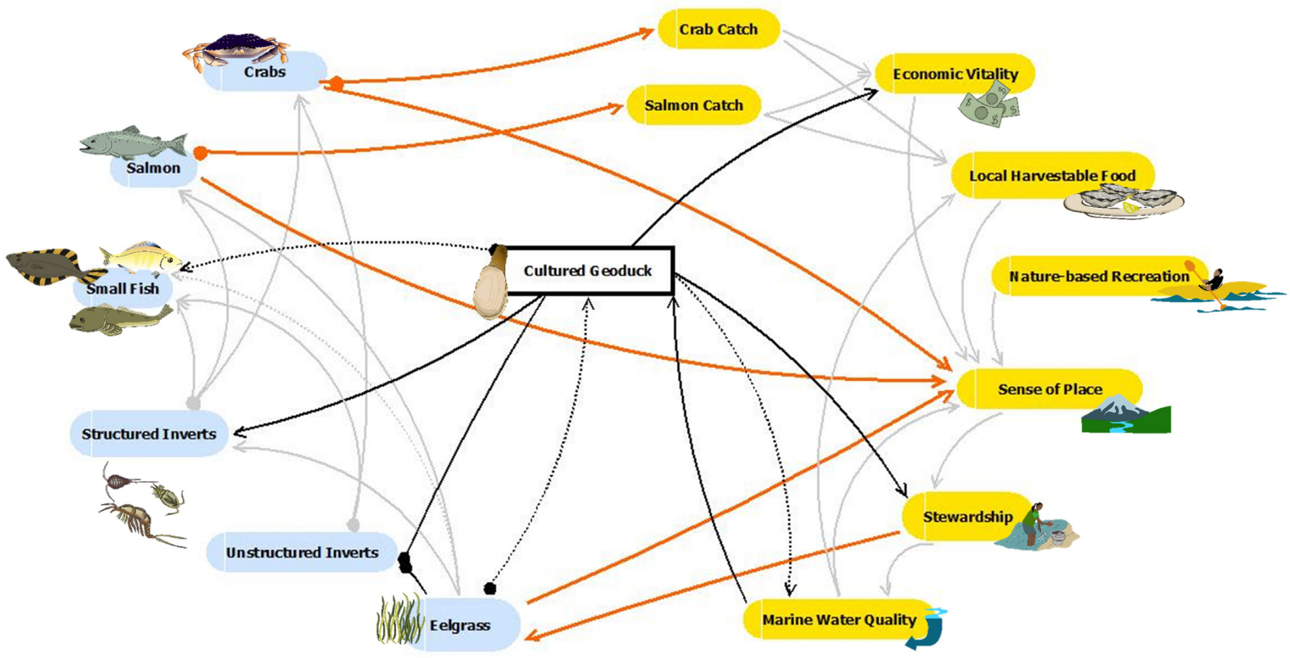

Figure 2. Digraph of the "Base" Geoduck conceptual model. Colors represent aquaculture (white), ecology (blue), and social (yellow) categories of variables. Links are positive (arrow) or negative (filled circle), and either certain (solid line) or uncertain (dashed line). The color of links signify connections that are interdisciplinary (orange), direct to Cultured Geoduck (black), and within disciplines (grey).

Table 1. Descriptions of variables included in all conceptual models. Descriptions with asterisks have been modified from the Puget Sound Partnership's original definitions to better suit the aquaculture focus of this study.

Variable	Description
Eelgrass	Sound-wide eelgrass area (*Zostera marina*)
Marine Water Quality	Levels of pollution in nearshore marine environment*
Unstructured Invertebrates	Abundance of marine invertebrates (deposit and filter feeders) that affiliate with unstructured habitats (e.g., mud flats)
Structured Invertebrates	Abundance of marine invertebrates (deposit and filter feeders) that affiliate with structured habitats (e.g., eelgrass, aquaculture grow-out gear)
Small Fish	Abundance of small nearshore fish including sculpin (e.g., Cottidae), flatfish (e.g., Pleuronectidae) and surf perch (Embiotocidae)
Crabs	Abundance of Dungeness and graceful crabs (*Metacarcinus spp*.)
Salmon	Abundance of salmon (*Oncorhynchus* spp.)
Scoters	Abundance of *Melanitta spp.*
Crab Catch	Fishery removals of Dungeness crabs (Cancridae)
Salmon Catch	Fishery removals of salmon (*Oncorhynchus* spp.)
Local Harvestable Food	Subsistence and recreational fishing and shell fishing*
Nature-based Recreation	Participation in kayaking, walking on beach, boating, swimming, bird watching, etc. in the Puget Sound region
Stewardship	Extent of caring for the Puget Sound marine environment*
Economic Vitality	Including employment in natural resource industries, percent employment in natural resource industries, and natural resource industry output
Sense of Place	Extent to which people identify with and feel positively attached to a specific place
Cultured Geoduck	Aquaculture effort to culture Pacific geoduck (*Panopea generosa*)
Cultured Manila Clams	Aquaculture effort to culture Manila clams (*Venerupis philippinarum*)
On-Bottom Oyster	Aquaculture effort to culture Pacific oysters (*Crassostrea gigas*) on the sediment

Water Quality and Stewardship) (Table 1). For simplicity, we use the term "social" in this study to represent this full list of social, economic, and other non-ecological variables in this model.

Model Linkages

In each model, a set of variables were connected by positive or negative links if a change in one was expected to cause an increase/decrease in the other. Uncertain links connecting two variables were included in the models when the direction of the relationship was known (negative or positive) but the scale or frequency of impact was not well-established. The social-ecological models only differed in their links between cultured shellfish variables and others in the models (with the exception of the clam model with the added *Scoter* variable).

We populated links between social variables based on expert elicitation and a review of the peer-reviewed and grey literature (Figure 2, Supp. Figs 1–3, Supp. Table 1). For the former, we interviewed four experts on the social dynamics of the shellfish aquaculture industry in the region. Expert knowledge is a widely used and useful technique in dynamic, complex systems that are data poor, yet require management decisions (Martin *et al*., 2012). A relatively low number of experts is justified for determining qualitative measures of a local system due to the need for specialized, region-specific knowledge (shellfish aquaculture in Puget Sound) (Kuhnert *et al*., 2010; Drescher *et al*., 2013). We identified and interviewed four experts who, due to their involvement in industry, training, research, or personal experience, were able to summarize information and perspectives on the social aspects of aquaculture (Burgman *et al*., 2011; Martin *et al*., 2012). Specifically, they included a tribal environmental health professional with expertise in the place-based cultural ecosystem services of shellfish and knowledge of first foods and tribal community health; a marine environmental economist with expertise in estimating the value of ecosystem services as part of the human dimension of coastal and nearshore environments; an environmental scientist with a non-profit institute whose portfolio includes biological, oceanographic, and social science research to evaluate sustainability of bivalve aquaculture production in nearshore environments; and a social scientist at a federal-university partnership program with expertise in social and cultural dimensions of coasts and oceans, experience developing human well-being indicators, and scholarship in subsistence practices and Indigenous and local knowledges. The literature review included studies that employed a wide range of methods (the complete list of studies is in the supplemental material). Ecological studies including a variety of ecological sampling and experimental designs, experimental work in lab settings, isotope analyses, meta-analyses, acoustics, and tagging. Social-ecological studies included participatory workshops, public surveys, analyses of economic data, various types of interview methods, and reviews of newspapers and other public media.

Expert elicitation augmented information obtained from review of the limited published literature on social aspects of aquaculture in the region. The experts were first asked to examine a diagram that depicted the linked ecological model and the social variables which were not linked to each other or the ecological variables. We then solicited comments from the experts on how they would define the social variables and how they would likely affect each other (positive, negative, or neutral). In addition to specifying linkages between social variables, experts were asked to link social variables to the ecological model. Links connecting social variables in the models represented positive or negative interactions, summarizing what was considered the common sentiment or perspective of Puget Sound communities (while acknowledging varying perspectives exist among subgroups, as discussed below).

Literature review included peer review literature, reports produced by federal and state agencies, and non-profits, and Masters Theses and Ph.D. Dissertations. Research conducted in the Puget Sound region, or other estuaries in Washington State and on the USA & Canadian Pacific coast, were prioritized if numerous studies were found. We relied solely on either published/grey literature or expert knowledge if only one source was available. If expert knowledge differed from the literature-based interpretation, we made a choice of one or the other based on the following: (i) which interpretation reflected trends across a broader temporal and spatial scale, within Puget Sound; and (ii) if one source provided greater context, filling in data gaps that have not been published or, conversely, are unknown to the expert. If both the expert knowledge- and literature–based interpretations could not be reconciled, we created an uncertain link in the model, meaning the direction of the relationship was known (negative or positive) but the scale or frequency of impact was not well-established.

Cultured shellfish beds add structure to the nearshore environment, including the shells themselves as well as the suspended lines and mesh bags, netting, tubing, and other materials associated with the grow-out phase of shellfish aquaculture. This structure benefits certain groups of species, and was represented by connecting cultured shellfish variables positively to structure-associated invertebrates, and negatively to invertebrates associated with unstructured habitat (Dumbauld *et al*., 2001; McDonald *et al*., 2015). No links were added between cultured shellfish variables and fish given the lack of published research on population level impacts (increasing or decreasing). Cultured shellfish variables had uncertain, negative links connected to *Eelgrass*, due to the general nature of the model (summarizing across various eelgrass metrics such as density and percent cover, and various aquaculture phases such as harvest and grow-out) and the range of levels of responses reported in the literature (summarized in Dumbauld *et al*., 2009; Forrest *et al*., 2009; Ferriss *et al*., 2019).

The cultured shellfish variables had positive effects on *Economic Vitality, Stewardship* (uncertain link), and *Marine Water Quality* (uncertain link). Uncertainty in the connection to *Stewardship* was based on the perceptions that shellfish growers care and work towards improving the marine environment, in part to ensure a healthy product, but they also introduce gear in the water, potentially contributing to marine debris and altering the nearshore landscape (Rudell, 2012; D'Anna and Murray, 2015; Hudson, 2016; Ryan *et al*., 2017). Uncertainty in the *Marine Water Quality* link is in recognition of the filter feeding capacity of shellfish, known to remove excess nutrients from the water, however the scale of impact on Puget Sound marine water quality is not well established (Gentry *et al*., 2020). *Marine Water Quality* has a positive effect on cultured shellfish variables as the industry is affected by various contaminant and harmful algal bloom events. Most social variables had a positive effect on *Sense of Place*, which had a positive effect on *Stewardship*. *Stewardship* contributed to increased habitat condition (*Marine Water Quality* and *Eelgrass*).

Connections between the ecological and social components of the model include the presence of iconic species (*Salmon* and *Crab*) contributing to *Sense of Place* and fisheries (*Salmon Catch* and *Crab Catch*) (van Putten *et al*., 2018). Fisheries (*Crab Catch* and *Salmon Catch*) had a positive effect on *Economic Vitality* and *Local Harvestable Food*. *Eelgrass*, representing ecological integrity, contributed to *Sense of Place* (Poe *et al*., 2016), and *Stewardship* positively linked to *Marine Water Quality*. For a description of all links, please refer to Figure 2, Supp. Table 1, and Supp. Figs. 1–3.

Multiple Geoduck Models

To evaluate how model structure based on stakeholder values may impact predictions, we developed an "Alternate" Geoduck social-ecological model, informed by expert elicitation and previous studies on the regional conflict around geoduck aquaculture (Rudell, 2012; Ryan *et al*., 2017). The two social-ecological Geoduck models differed in their links connecting *Cultured Geoduck* to the *Stewardship* and the *Nature-based Recreation* variables. These two variables are common areas of conflict highlighted in interviews of people interested in aquaculture in South Puget Sound and filed in geoduck aquaculture permit application cases before Washington State Hearings Boards (Shorelines Hearings Board, Growth Management Hearings Board, Pollution Control Hearings Board) (Rudell, 2012; Ryan *et al.*, 2017). While this case study represents local issues, Ryan *et al.* (2017) also document how ecological and recreational concerns are present in aquaculture conflicts in other regions of the USA and globally.

The “Base” Geoduck model (the Geoduck social-ecological model used in the prior analysis) represents the perceptions that *Cultured Geoduck* has positive effects on *Stewardship* and no effect on *Nature-based Recreation*. The perspectives represented by the “Base” Geoduck model consider those who work in aquaculture to be more invested in protecting water quality and surrounding environmental conservation efforts, as it directly impacts their livelihood. In the “Base” Geoduck model, aquaculture does not impact recreation on any significant scale. While we recognize these perspectives are represented by a more complex group than described by Rudell (2012), the authors describe this group as generally consisting of aquaculture growers, academic research scientists, federal, state, and tribal managers, and tribe members, based on a limited list of survey participants. The “Alternate” Geoduck model (Supp. Figure 3) represents those that perceive geoduck aquaculture negatively with regard to its impact on the environment (*Stewardship*), through the production of marine debris (e.g., dislodged or errant PVC pipes used in grow-out gear), and in terms of *Nature-based Recreation*, restricting pedestrian and recreational boater beach access (e.g., launching/landing of recreational boats). Members of this group include waterfront landowners, non-governmental organization members, and academic scientists (Rudell, 2012). Their perceptions were represented in the “Alternate” Geoduck model by negatively linking *Cultured Geoduck* to *Stewardship* and *Nature-based Recreation*.

Qualitative Network Models: Predicting How Variables Change

Qualitative network models (QNMs) were used to compare differences in system responses implied by the different conceptual models. To do so, the conceptual models were recast as signed digraphs, or digraphs which consist of nodes (social-ecological variables) and edges (links) that indicate the sign of the effect of one variable on another (positive, negative, or neutral). In matrix form, digraphs correspond to the community matrix, **A**, the elements of which represent interaction strengths (Puccia and Levins, 1985). At their core, QNMs are based on analysis of **A**. If the elements of **A** are specified quantitatively, the effect of a press perturbation on one or a subset of variables can be obtained from - $\mathbf{A}^{-1}$, which conveys the relative change in the level of variables composing the system at equilibrium (e.g., Bender *et al.*, 1984). However, quantitative estimates of **A** are rarely available, and can be challenging to obtain in even a simple system (Dambacher *et al.*, 2003).

In QNMs, the signs of interaction strengths (as specified by the digraphs) are retained in **A** but interaction strengths are sampled from uniform probability distributions reflecting high uncertainty in their magnitude (Raymond *et al.*, 2011; Melbourne-Thomas *et al.*, 2012). The sign responses of system variables are averaged across a large number of simulations (10^4) and sign consistency is used to characterize uncertainty. The approach essentially explores whether information in the form of a specified network structure is sufficient to gain insight into system responses to perturbations (Levins, 1998).

Specifically, we utilized the simulation routine of Melbourne-Thomas *et al.* (2012), which also permits incorporation of structural uncertainty related to the presence or absence of uncertain linkages. First, the presence of linkages in the network that were designated as uncertain was sampled from a binomial distribution. The probability of presence was set to 0.5 following previous studies (Melbourne-Thomas *et al.*, 2012; Reum *et al.*, 2015b). Second, the elements of **A** corresponding to the present linkages were sampled from uniform probability distributions spanning two orders of magnitude (0.01 to 1) but the sign of the link was maintained. If the realized **A** passed stability criteria (Melbourne-Thomas *et al.*, 2012) it was retained. The procedure was repeated until 10^4 stable matrices were obtained. The set of retained, stable matrices was used to characterize uncertainty in outcomes to press perturbations (Melbourne-Thomas *et al.*, 2012). We reported sign consistency as the percent of simulations that resulted in either positive, zero, or negative changes in each variable (no support/uncertain: 50–69%, support: 70–100%) (e.g., Raymond *et al.*, 2011; Zador *et al.*, 2017). For example, if 83% of the simulations predict that *Economic Vitality* will increase as *Cultured Geoduck* increases, then that is interpreted as support for a predicted increase in that variable. We selected a higher minimum level of sign consistency (70%) relative to some other publications (e.g., 60%: Martone *et al.*, 2017; Sobocinski *et al.*, 2018) to focus on results with higher prediction certainty according to sign agreement (level of agreement among model simulations in predicting positive, zero, or negative changes in a given variable) (Reum *et al.*, 2019; Reum *et al.*, 2020).

Model Comparisons

The ecological, social, and integrated QNMs for each of the four types of aquaculture were perturbed under an expanded aquaculture scenario. That is, the cultured shellfish variable (i.e., *Cultured Oyster On-Bottom*, *Cultured Oyster Off-Bottom*, *Cultured Clam*, or *Cultured Geoduck*) in each model was positively pressed. First, we compared the predicted outcomes of aquaculture expansion from the separate ecological and social models relative to the integrated models, for each type of aquaculture. We then compared the four social-ecological models (Clams, Oyster On-Bottom, Oyster Off-Bottom, and “Base” Geoduck), to identify differences in tradeoffs across aquaculture types. Last, we compared predicted outcomes from the “Base” and “Alternate” social-ecological Geoduck models.

Uncertainty analysis knowledge gap identification

We used the integrated “Base” Geoduck model to evaluate whether variables responded to aquaculture expansion in a similar manner and to evaluate the influence of uncertain linkages on model outcome. We conducted this analysis on the “Base” Geoduck model only, as this was the focus of more in-depth analysis in this study (comparison between the integrated and the ecological and social models, and comparison between the “Base” and “Alternate” models). To evaluate influence of uncertain linkages, we calculated the difference in the sign outcomes of variables between models with and without a given uncertain link, under an expanding geoduck aquaculture scenario. If linkages strongly influence sign

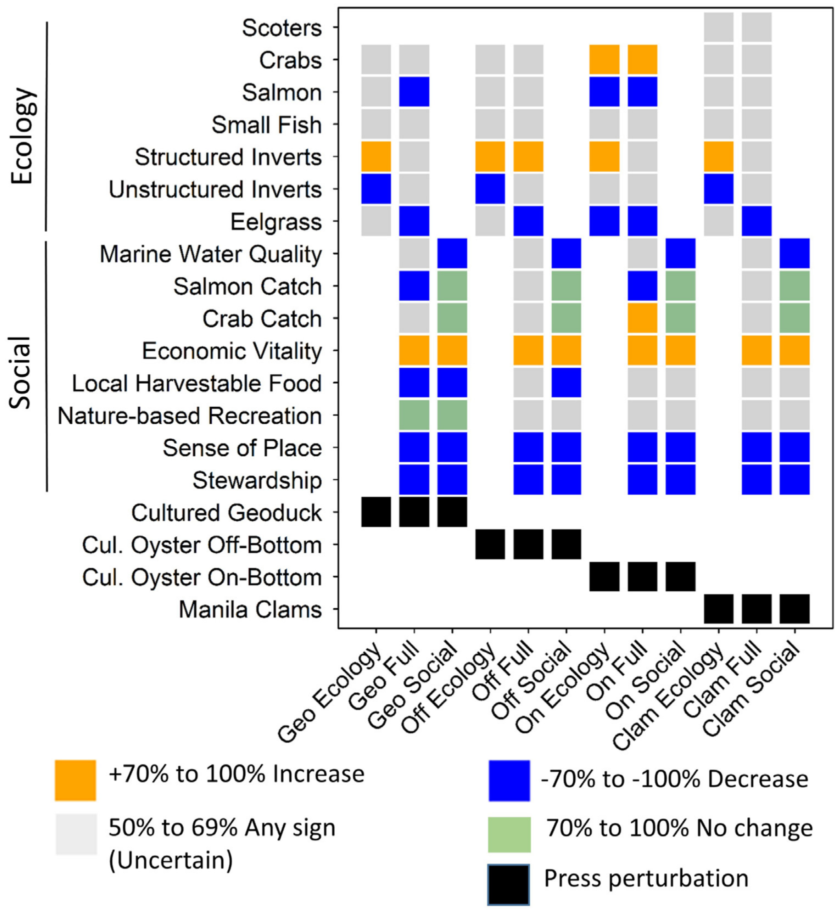

Figure 3. Sign response of each variable in the qualitative network models to increases in Cultured Geoduck (in model signified by "Geo"), Cultured Oyster On–Bottom (in model signified by "On"), Cultured Oyster Off-Bottom (in model signified by "Off"), and Cultured Manila Clam (in model signified by "Clam") aquaculture in the social-ecological models (full), models with only ecological nodes ("Ecology"), and models with only social nodes ("Social"). Results for the "Base" Geoduck model are presented (negative links from Cultured Geoduck to Nature-based Recreation and Stewardship). Colors represent strength of the predicted trend (sign consistency, or the percent of simulations that resulted in either positive, zero, or negative changes in each variable), represented by the squares filled with grey (50% to 69% any sign; uncertain), orange (+70% to 100%; increase), blue (−70% to 100%; decrease), and green (70% to 100%; no change). Black squares represent the press perturbation for each scenario.

outcomes it suggests they represent an important knowledge gap and potential research priority.

Results

Simulations

Individual social or ecological models versus social-ecological models

Outcomes from the ecological models differed from the social-ecological models for one to four variables (Oyster On-Bottom and Geoduck models, respectively) (Figure 3). For instance, *Salmon* predictions switched from uncertain to negative between the Geoduck ecological and social-ecological models (Figure 3). Exploration of this model result determined the trend was linked to reduced prey (*Structured Invertebrates* changed from positive to uncertain, due to decreased *Eelgrass*) and increased mortality from the addition of *Salmon Catch* from the social variables. In another example, *Unstructured Invertebrates* had sign consistency support for a decrease in the ecology models but uncertain predicted outcomes in the social-ecological models (except in the Oyster On-Bottom model). Interestingly, *Eelgrass* was predicted to decrease in the social-ecological model, relative to low sign consistency in the ecology models ("Base" Geoduck model, Oyster Off-Bottom model, and Clam model), reflecting indirect effects from the social variables, including *Stewardship* and *Sense of Place* (Figure 3).

The predicted outcomes of social variables also changed between the social and social-ecological models by two to four variables (Geoduck/Oyster On-Bottom and Oyster Off-Bottom, respectively). *Water Quality* switched from uncertain sign consistency in the social-ecological model to a predicted decrease in the social model across all aquaculture types, except Oyster On-Bottom (Figure 3). *Salmon Catch* and *Crab Catch* had sign consistency for no change in the social models, reflecting a lack of ecological feedback to influence catch in the model (i.e., no variables representing salmon and crab populations). Similarly, *Nature-based Recreation* had no link leading to it from the rest of the "Base" Geoduck model (sign consistency for no change) whereas it had an uncertain negative link from *Cultured Clams, Cultured Oyster On-Bottom, and Cultured Oyster Off-Bottom*, in the other models, resulting in low sign consistency for either increase or decrease in the predicted outcome. *Sense of Place* was predicted to decline in both social and social-ecological models, in

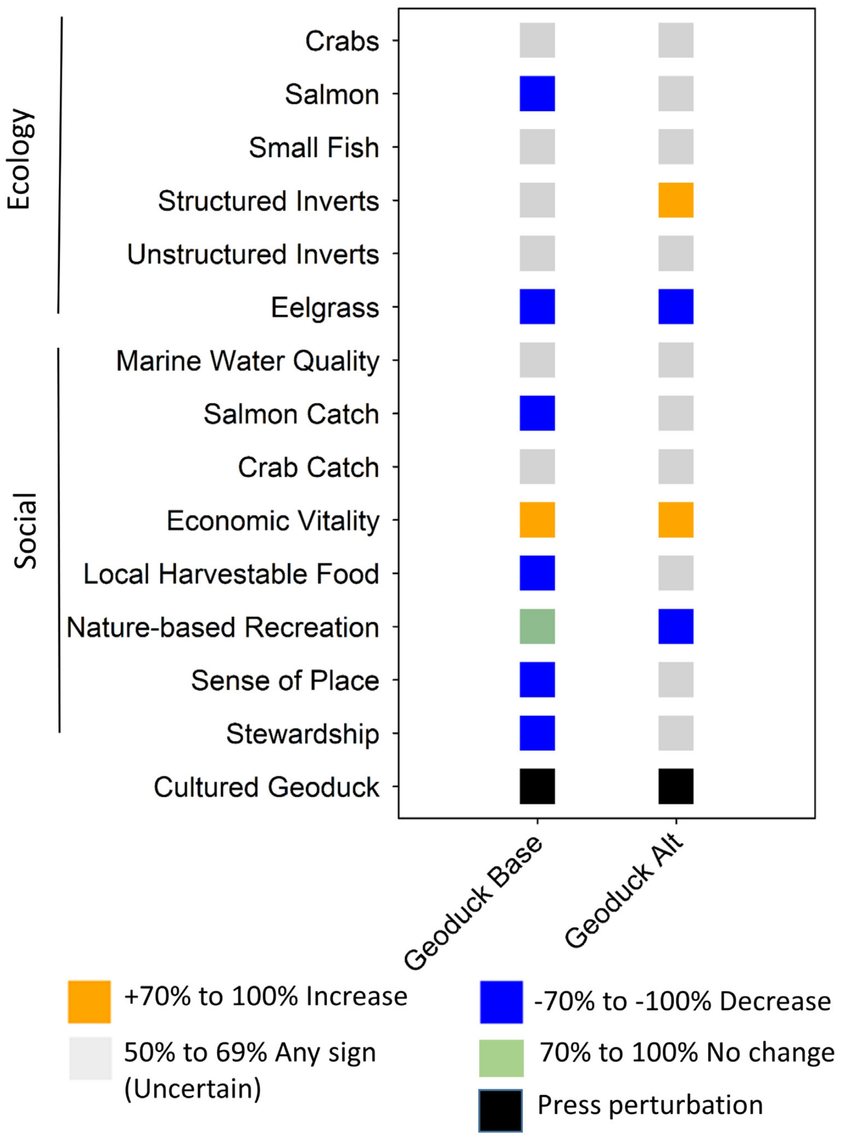

Figure 4. Response of each variable to increases in Cultured Geoduck in the "Base" and "Alternative" Geoduck models. Blue represents a decrease and orange an increase. Colors represent strength of the predicted trend (sign consistency, or the percent of simulations that resulted in either positive, zero, or negative changes in each variable), represented by the squares filled with grey (50% to 69% any sign; uncertain), orange (+70% to 100%; increase), blue (–70% to 100%; decrease), and green (70% to 100%; no change). Black squares represent the press perturbation for each scenario.

all aquaculture models (Figure 3). Exploration of these model results show that *Stewardship* corresponds to the predicted signs (increase or decrease) of *Sense of Place*, and *Eelgrass* and *Marine Water Quality* correspond to the predicted sign of *Stewardship*.

Comparisons Between Aquaculture Methods

Increases in the cultured shellfish variables of the four social-ecological aquaculture models ("Base" Geoduck, Clam, Oyster Off-Bottom, and Oyster On-Bottom) predicted changes across a range of variables (Figure 3). All social-ecological models supported an increase in *Economic Vitality* and decreases in *Eelgrass*, *Sense of Place*, and *Stewardship*. The Clam and Oyster Off-Bottom models had the most variables with low sign consistency (11 of 15 and 9 of 14 variables, respectively). The Oyster On-Bottom model had sign consistency supporting increases in the most variables (*Crabs, Crab Catch*, *Economic Vitality*), and sign consistency for change (increase and decrease) in the most social variables (six), including changes in *Crab Catch* (increase) and *Salmon* (decrease). "Base" Geoduck and Oyster On-Bottom models had sign consistency for decreases in the most variables (six), including *Salmon*, *Eelgrass*, *Salmon Catch*, *Sense of Place*, *Stewardship*, *Local Harvestable Food* ("Base" Geoduck model only), and *Marine Water Quality* (Oyster On-Bottom model only).

Multiple geoduck conceptual models

The changes in model structure between the integrated "Base" and "Alternate" Geoduck models resulted in changes primarily in predicted sign consistency and sign determination in the social variables (five of eight variables) (Figure 4). The "Base" Geoduck model predicted decreases in *Stewardship, Sense of Place, Local Harvestable Food, Salmon Catch,* and *Salmon*.

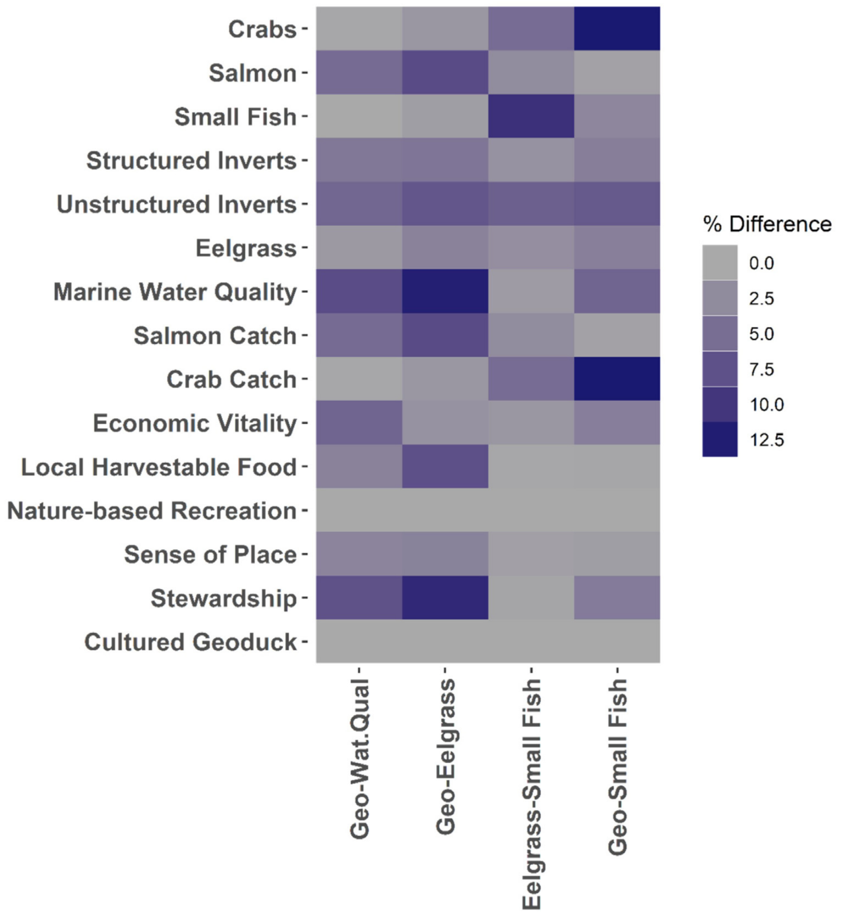

Figure 5. Sensitivity in sign consistency of each variable (*y*-axis) to the uncertain links in the socialecological "Base" Geoduck model (x-axis). "Geo" represents the Cultured Geoduck variable on the *x*-axis. Grey scale represents percent change in the sign consistency (reduced model – full model) of predicted outcomes for each variable when the link (labelled on the *x*-axis) is removed from the model.

There was no sign consistency supporting any corresponding direction of change for those variables in the "Alternate" model. Decreases in *Eelgrass* and increases for *Economic Vitality* were predicted in both models. *Nature-based Recreation* had sign consistency for no change in the "Base" model and a decrease in the "Alternate" model, reflecting the removal of an uncertain, negative link from *Cultured Geoduck* in the "Base" model (and no other links leading to that variable). Further exploration of the model connected this result to the influence of *Sense of Place*. For the remaining variables, outcomes were similarly uncertain between models.

Knowledge gap identification

Sensitivity to uncertain links resulted in a maximum percent change in sign consistency of 11.5% (Figure 5). The variables with a change in sign consistency of greater than 10% when an uncertain link was removed included *Crab* and *Crab Catch* (*Cultured Geoduck* to *Small Fish* link), *Marine Water Quality* and *Stewardship* (*Cultured Geoduck* to *Eelgrass* link), and *Small Fish* (*Eelgrass* to *Small Fish* link). As a whole, the uncertain link with the greatest influence across the model was the *Cultured Geoduck* to *Eelgrass* link followed by the *Cultured Geoduck* to *Small Fish* link (they produced the greatest proportion change when summed across all variables, i.e. summing each column in Figure 5).

Discussion

Integrated social-ecological models of bivalve aquaculture can improve our understanding of the system as a whole, highlight how different perspectives can inform this understanding, identify potential tradeoffs across aquaculture methods, and identify key knowledge gaps. Our results highlight how predictions of variable responses to aquaculture expansion can differ depending on whether characterization of the system is limited according to discipline or integrates across disciplines. While single discipline models did not provide opposite results to social-ecological models (complete sign change between increase and decrease), the change in certainty might influence priorities in research and policy decisions. In addition, we show that changing model structure to represent different perspectives on how aquaculture interacts with the surrounding social system can also influence predicted outcomes, highlighting the importance of recognizing potential bias in model structure. Our results are in agreement with recent work by Johnson *et al.* (2019) in that a social-ecological system approach to aquaculture research and management would help advance efforts to sustainably develop the industry.

Predictions under the social-ecological model differed relative to the separate ecological and social models, and demonstrated the interconnected nature of ecological and social components in the aquaculture system (Liu *et al.*, 2015). Variables became more or less uncertain between the models; however, no variables completely switched signs (between increase and decrease with a 70% consistency). For example, the sign outcome of *Eelgrass* changed from uncertain to negative between the ecological models and the social-ecological models for all types of aquaculture except Oyster On-Bottom. The inclusion of mechanisms influencing *Eelgrass* populations from the ecological perspective (physical interaction with aquaculture) and the social perspective (varying levels of *Stewardship*) provide a more holistic view of the aquaculture social-ecological system. In another example, the uncertain negative link connecting *Cultured Geoduck* with *Eelgrass* directly (via habitat) and indirectly (via prey) in the conceptual model negatively influenced *Salmon* and thus *Local Harvestable Foods*, and ultimately *Sense of Place* in the QNM results. Our results agreed with Zador *et al.* (2017), demonstrating the value of including interdisciplinary aspects of a system to better account for all the direct and indirect interactions that can occur. This integrated approach is informative for systems that are continually evolving in response to changing industry practices (e.g., shifts in methods and cultured species), management decisions (e.g., protected species policies), coastal development, and ocean conditions (Holling, 1998).

Stakeholders can differ fundamentally in their perceptions regarding the ecological and social interactions of bivalve aquaculture (D'Anna and Murray, 2015; Hudson, 2016; Froehlich *et al.*, 2017; Mather and Fanning, 2019). The changes in two social links between our "Base" and "Alternate" Geoduck models resulted, primarily, in changes in predicted sign agreement and sign determination in the social variables (six of eight variables). Stier *et al.* (2017) concluded that experts filling ecological data gaps could influence model results due to differences in understanding of the system in question. Our study adds to this premise by showing how social-ecological models structured to reflect different perspectives and values regarding aquaculture can also influence predictions of the social-ecological system response. It is important to note, however, that the models in this study omit numerous perspectives, such as the relationship between indigenous peoples and cultured shellfish (Donatuto *et al.*, 2011; Poe *et al.*, 2014; Breslow *et al.*, 2016; Donatuto *et al.*, 2016; Hicks *et al.*, 2016). A suite of models representing the full range of group perspectives in aquaculture through a multiple model framework could identify areas of conflict (different predictions), areas of agreement (similar predictions), and help determine if differences are values-based or can be resolved with additional research. Modeling the aquaculture system from a range of perspectives acknowledges uncertainty about the existence of any single representative model, increases transparency regarding whose perspectives are represented in the model, and helps identify potential biases in model structure, underlying assumptions, and, ultimately, predictions (Liu *et al.*, 2007; Raymond *et al.*, 2011; Stier *et al.*, 2017). Overall, engaging broader groups of stakeholders and management groups in model creation, which involves both facts and values, can help enhance trust and communicate results (Gray *et al.*, 2012; Dietz, 2013).

This modeling framework is also useful for identifying and prioritizing knowledge gaps through a sensitivity analysis of our pre-determined uncertain links (e.g., *Marine Water Quality*), and by generating new questions about our understanding of the system from the results (e.g., *Sense of Place*). Of the uncertain links in the "Base" Geoduck model, the *Cultured Geoduck* and *Small Fish*, and *Cultured Geoduck* and *Eelgrass* links were the most influential (produced the greatest change across all variables when removed), suggesting increased certainty in these relationships would improve the model as a whole. Research indicates the response of eelgrass to shellfish aquaculture can vary depending on the metric of interest (e.g., density or percent cover), regional environmental conditions, type and phase of aquaculture (e.g., harvesting or grow-out), and other factors (summarized in Dumbauld *et al.*, 2009; Forrest *et al.*, 2009; Ferriss *et al.*, 2019). A more nuanced understanding of the uncertainty in links to *Eelgrass* could be achieved by comparing models that were more regionally specific, reflecting context-specific interactions. Other model results that had less clear mechanisms of explanation could also be examined in this context to identify nuances or complexities in their model connections that could be improved in future model iterations.

Another example of identifying knowledge gaps from model results is *Sense of Place*. The *Sense of Place* variable had sign consistency for a decreasing trend across all models. The variable is highly connected in the model (eight links) and can vary depending on the perspectives of different stakeholders and groups (e.g., Poe *et al.*, 2016). *Sense of Place* results were due to the support for decreases in the majority of variables directly connected to it (*Salmon, Local Harvestable Food, Marine Water Quality*, and *Eelgrass*) which was counter-intuitive in contexts such as the Geoduck "Base" model (D'Anna and Murray, 2015). This is an example where a model can help further the conversation of how *Sense of Place* is represented and interpreted, and how aquaculture contributes to *Sense of Place* in the context of other natural and social factors (e.g., presence and availability of salmon, habitat integrity, and recreational opportunities). Identification of these interdisciplinary knowledge gaps help provide an integrated focus on outstanding lists of aquaculture research needs in the region (Pacific Shellfish Institute, 2015; Breslow *et al.*, 2019).

Challenges in the development of interdisciplinary conceptual models included the selection and definition of the variables and links, navigating differences in the scale of the variables, representing how different user groups perceive the impacts of shellfish aquaculture, and agreement on a subset of ecological and social variables to represent the aquaculture system. Many of our discussions about priorities and perceptions of the system informed the inclusion of uncertain links in the model, others led to the creation of separate models to represent different world views (e.g., the *Cultured Geoduck* and *Nature-based Recreation* link), and some must be resolved with additional research (e.g., the *Cultured Pacific Oyster On-Bottom* and *Marine Water Quality* link). Deliberations included why certain aspects should be included/excluded in the model, whether variables should be broadly grouped (e.g., *Economic Vitality*) or included separately (e.g., *Eelgrass*), and whether relationships were significant enough to delineate in the model (e.g., the impact of shellfish on *Marine Water Quality* at a broad geographic scale). Our decisions were influenced by data availability, the relative importance of ecological, management, or social realms, our starting list of selected indicators, and our selection of experts in the expert-elicitation process (and the perspectives they were capable of summarizing). For example, we discussed dividing *Economic Vitality* into more specific indicators such as natural resource-based jobs and local economic metrics, to avoid aquaculture trends being lost in this broad category. Geographic scale of interaction was debated for the potential negative relationship between cultured shellfish variables and *Nature-based Recreation* (e.g., exclusion of boating access to a beach) and for the potential positive impact of shellfish on *Marine Water Quality*.

This case study identifies a tool that can be further developed and applied to the management of Puget Sound shellfish aquaculture. Adoption of QNMs requires adequate buy in from stakeholders and managers, and additional engagement will be crucial for establishing QNMs as a viable tool for aquaculture management in the region. The models developed in this study could be improved further and eventually inform strategic decision-making. In this initial effort, we have highlighted some areas that should be prioritized in the next round of development that could be used in management. For example, input from various community groups and further understanding of key variables such as sense of place. Similar applications of QNMs have been used to engage communities in fisheries management (Reum *et al.*, 2019). This work can also inform the perspective of the Puget Sound Partnership (PSP), which is the state program leading the region's collective effort to restore and protect Puget Sound, through our demonstration of the connection between PSP's vital signs (the basis for the social-economic components of our QNM models) and direct action taken on shellfish aquaculture. Thus, PSP could benefit from understanding how changes in an important resource-dependent industry (shellfish aquaculture) impact the identified vital signs and thereby influence the organization's recovery goals.

While we purposefully used a predefined list of Puget Sound indicators as a starting point for selecting social indicators, this approach also influenced omissions in our model. Future iterations of these models could consider a wider range of social science variables, such as equity, sense of agency, governance, health, safety, resilience, and human well-being (Donatuto *et al.*, 2011; Poe *et al.*, 2014; Breslow *et al.*, 2016; Donatuto *et al.*, 2016; Hicks *et al.*, 2016). In addition, as mentioned above, the experts and literature consulted to create the models represent or exclude interest groups, ecological species, or perspectives, presenting additional challenges (and opportunities) for model development (Donatuto *et al.*, 2016; Holden *et al.*, 2019). Without the broad acceptance of these models by the community of managers, industry, and other stakeholders, these results should not be considered for policy recommendations, but rather as an opportunity to advance research and conversations around aquaculture expansion.

Ecosystem approaches to shellfish aquaculture can benefit from explicitly recognizing humans as integral components of ecosystems, and the connections between social and ecological aspects of the system (Lubchenko, 1998; Soto, 2007; Ostrom, 2009; Poe *et al.*, 2014; Charnley *et al.*, 2017; Brugère *et al.*, 2018; Johnson *et al.*, 2019). Ecosystem approaches to management have increasingly underscored the value of developing conceptual models to clarify and organize thinking regarding complex social-ecological systems (Harvey *et al.*, 2016; Levin *et al.*, 2016). As we show here, these conceptual models can also be formalized as QNMs to help understand the causal connections between the sources of disturbance and the ecosystem components of interest (Puccia and Levins, 1985; Dambacher *et al.*, 2003). This approach can aid in our continued understanding and sustainable development of aquaculture systems.

Author Contributions

All authors contributed to the development and methodology of the study. BEF, PSM, BLS conducted interviews as part of the expert-elicitation process. BEF compiled the literature for the conceptual models. All authors contributed to analyses of findings as well as drafting and revising the manuscript.

Supplementary Data

Supplementary material details of each model are provided in the supplemental material.

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Conflict of interest

The authors of this study certify that they have no affiliations with or involvement in any organization or entity with any financial interest, or non-financial interest in the subject matter or materials discussed in this manuscript.

Data Availability Statement

The data underlying this article are available in the article and in its online supplementary material.

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