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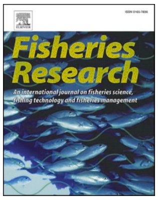

Full length article

Using participatory conceptual modeling to integrate ecosystem and socioeconomic information into the fisheries stock assessment process: A Gulf of America red snapper case study

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A B S T R A C T

Fisheries stock assessments are the backbone of fisheries management in the United States. While a stock assessment model provides scientific estimates of stock status and overfishing limits, the broader process involves decisions about which data are collected, how the model is structured, and the social and economic effects of implementing the quota advice. Despite growing recognition that ecosystem and socioeconomic factors strongly influence fish stocks and fisheries, these drivers remain underrepresented in the assessment process. In the current period of rapid global change, environmental disturbances and anthropogenic impacts are increasing in frequency and intensity, escalating the need for stock assessments to explore and account for the complex dynamics among fish stocks, fisheries, and social systems. In our research, we illustrate how participatory conceptual modeling can improve the entire stock assessment to management process by identifying data gaps, elucidating changes in fishing activity and human behavior over time, providing context to help explain model uncertainty and improve model parameterization, and describing feedback loops and unintended consequences of management actions. A case study from the Gulf of America red snapper (*Lutjanus campechanus*) fishery is used to illustrate the benefits of this methodology. Encouraging participatory conceptual modeling alongside future stock assessments would greatly increase our understanding of the socio-ecological feedbacks that are often critical to management success, and help determine how best to manage fisheries through an ever changing environmental and human landscape.

1. Introduction

In the United States, stock assessments are the primary scientific tool used to inform sustainable fisheries management (Beverton, 1957; Hilborn and Walters, 1992; Lynch et al., 2018). At their core, stock assessment models analyze data on catch, abundance, and biology to estimate stock status and fishing mortality, producing outputs such as overfishing limits and biological reference points. However, while the model is central, the stock assessment process encompasses a broader continuum—ranging from data collection and processing, to model development, to management decisions based on assessment model results (Chan et al., 2022; Lynch et al., 2018; National Research Council, 2006).

Improving this full process has been an ongoing priority, with advancements in data sources, modeling techniques, and communication strategies (Punt, 2023). However, there remains ample room for improvement, especially considering increasing global demand and competition for fish resources (Felizola Freire et al., 2020; Naylor et al., 2021; Spijkers et al., 2021), the rapid pace of global change (Forster et al., 2024), and concerns about public trust in science (Lupia et al., 2024). NOAA's Stock Assessment Improvement Plan (SAIP) outlines a national framework for advancing assessments, and emphasizes the need to better account for ecosystem and socioeconomic drivers that shape fishery dynamics (Lynch et al., 2018).

Fisheries are complex social-ecological systems, and can be affected by a range of external forces—from environmental variability and

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habitat changes to fuel prices and labor markets (Leslie et al., 2015). While some of these drivers may be implicitly accounted for in model parameter estimates, they are not routinely or systematically incorporated into stock assessments. Furthermore, there are many external forces and social and economic considerations that are highly relevant to how quotas get implemented but that are often buried in the amendment process and ignored. The need to better understand and incorporate such factors was further underscored in the SocioEconomic Aspects in Stock Assessments Workshop (SEASAW) report, developed by NOAA Fisheries in 2020 with the goal of reviewing current practices for incorporating socioeconomics into the stock assessment process and providing recommendations for future action (Chan et al., 2022).

Ecosystem and socioeconomic variables are routinely considered at various stages of the assessment process. For example, external factors like fuel and export prices are being more commonly considered when standardizing fisheries catch-per-unit-effort data for use as inputs to assessment models (e.g., Kim et al., 2025). Recent reviews suggest that ecosystem variables are also increasingly considered in assessment models. However, the scope for inclusion of these drivers remains limited, and they are primarily considered on an ad hoc basis (Marshall et al., 2019). Similarly, there is some precedent for considering ecosystem and socioeconomic indicators alongside stock assessment model results when making harvest decisions, such as the use of risk tables (Dorn and Zador, 2020). Ecosystem and Socioeconomic Profiles (ESPs; Shotwell et al., 2023) synthesize key environmental and socioeconomic indicators for individual stocks, offering a broader context to managers during the stock assessment cycle. However, ESPs are broad in scope by design and do not detail how to integrate the indicator information into the stock assessment process. Although case studies (e.g., Shotwell and Dame, 2024) show potential for deeper integration, clear guidance is still lacking on how to identify which external variables matter, where they should be incorporated in the assessment framework, and how to balance trade-offs between diverse societal goals. Without structured approaches, valuable contextual information may be overlooked. As fishery systems face intensifying pressures, there is a need to expand the toolkit available for understanding and communicating stock dynamics within their broader ecological and human context.

One promising pathway for expanding the assessment toolkit is through structured engagement with stakeholders, whose knowledge and experience offer critical, yet often underutilized insight into both ecological and socioeconomic drivers (Anadón et al., 2009; Gervasi et al., 2022; Hind, 2015; Johannes et al., 2000; Sagarese et al., 2021). Fisheries resource users possess localized ecological knowledge informed by direct experience, often over generations (Bentley et al., 2019; Morrill, 1967; Renck et al., 2023; Silvano and Valbo-Jørgensen, 2008; Silvano and Begossi, 2012). Their insights can reveal behavioral patterns, spatial dynamics, and unintended effects of management, and can help define practical interpretations of goals like optimum yield (Malvestuto and Hudgins, 1996; Salgueiro-Otero and Ojea, 2020). While there are typically many avenues for stakeholder input into the stock assessment process (e.g., in the data collection stages, as part of advisory panels, or during public comment), this input is typically opportunistic and may be delivered in a non-neutral setting and thus may give an incomplete or biased view of the system.

Participatory modeling is a broad methodology that uses stakeholder knowledge to co-create models of complex systems (Quimby and Beresford, 2023). The method capitalizes on the understanding that stakeholders, through their constant interactions with ecosystems, can be considered system experts, and it is particularly well-suited to representing the complexity of fisheries and identifying key interactions (Lopes and Videira, 2017). Participatory modeling has proven effective in natural resource contexts, including shellfish aquaculture (Gourguet et al., 2021) and nutrient management (Franzén et al., 2011), where it has helped identify leverage points and communicate scenarios to stakeholders. Although interest is growing in using conceptual models (with or without stakeholder input) to structure stock assessments (Minte-Vera et al., 2024), the use of participatory modeling specifically to inform the components of stock assessments remains limited.

This study addresses that gap by evaluating how participatory modeling can provide a structured and transparent framework for integrating ecosystem and socioeconomic information into all stages of the stock assessment process. We generally used the SocioEconomic Aspects in Stock Assessments Workshop (SEASAW) report as a guide, as it provides a useful structure for evaluating where and how participatory methods can be applied to the entire stock assessment process (Chan et al., 2022). While a stock assessment model provides scientific estimates of stock status and overfishing limits, the broader process involves decisions about which data are collected, how the model is structured, and the social and economic effects of implementing the quota advice through combinations of input and output controls. We argue that each of these steps are critical to the success of the stock assessment enterprise, and each can be improved with additional consideration of external drivers.

We illustrate the approach with a Gulf of America (formerly Gulf of Mexico, hereafter Gulf) red snapper (*Lutjanus campechanus*) case study. Red snapper is a reef-associated finfish species found throughout the Gulf and along the eastern coasts of the Americas. It sustains one of the most economically valuable fisheries in the Gulf (Karnauskas et al., 2017) but faces numerous management challenges. Following a collapse of the stock in the 1980s due to overfishing, it has undergone a long-term rebuilding plan (Cowan et al., 2011). In recent years, artificial reefs have been deployed extensively—especially in the central Gulf—to increase both fish populations and fishing opportunities, yet the ecological consequences of this engineered habitat remain unclear (Gardner et al., 2022). Strict regulations and allocation frameworks have contributed to persistent conflict between commercial and recreational sectors. The recreational red snapper fishery is particularly substantial, and has been allocated about half of the quota since 1990 (NOAA Fisheries, 2025). U. S. fisheries are managed using the concept of optimum yield, which is defined as maximum sustainable yield reduced by a certain amount based on ecological, economic, and social goals (Malvestuto and Hudgins, 1996). However, we still lack a complete understanding of what optimum yield means for fisheries like red snapper and how best to manage for it (Hare, 2020). For example, fishermen may prefer to see effort reduced such that they are able to catch fewer fish overall, but the resource is more reliably available (Hanselman et al., 2007; Vaz et al., 2025). In addition to the results from stock assessment models, managers also need to consider such nuances in fishing industry objectives when making management decisions.

The importance of the red snapper resource and variety of interacting dynamics in the fishery underscore the need to fully understand and account for socio-ecological drivers that affect both population dynamics and human behavior. Here, we outline a standardized yet flexible approach for using participatory modeling to integrate socioeconomic and ecosystem information into the stock assessment process. We illustrate the approach using the red snapper case study and describe the benefits, lessons learned, and considerations for future research.

2. Methods

2.1. Participatory conceptual modeling

Our goal for this research was to use a participatory process to create a conceptual model of the Gulf red snapper fishery that could be used to inform stock assessment. To create the conceptual model, we wanted to begin with a blank slate, and have the model informed only by the perceptions of fisheries resource users (system experts). In typical citizen science participatory modeling projects, conceptual models are built collaboratively during in-person workshops, where participants write down system components on pieces of paper and place them on a central board. Linkages are then drawn between the components and revised during discussions (McPherson et al., 2022). We originally planned to use the same approach for this study, but due to travel restrictions surrounding the COVID-19 pandemic (Ciotti et al., 2020), fishermen were consulted for this project via semi-structured interviews following the methods of Clay and Colburn (2020), rather than in-person workshops. Knowledgeable red snapper commercial, recreational, and charter-for-hire fishermen throughout the Gulf were identified via multiple "entry points" to ensure to the extent possible that a diversity of opinions was accessed. Contacts were recommended by state agencies, the Gulf of Mexico Fisheries Management Council (Gulf Council), NOAA Fisheries, and snowball sampling (Atkinson and Flint, 2001). From these contacts, we attempted to balance individuals who have been regularly involved in the management process with those who have not. Additionally, we searched the internet for charter-for-hire captains, fishing clubs, and other businesses to find individuals who are not a part of the abovementioned network. Finally, at the end of the interviews, we asked fishermen to recommend other contacts who might have differing opinions on the fishery, to help ensure that snowball sampling would not result in a limited set of perspectives.

We began by identifying hotspots of red snapper fishing effort by considering published analyses (e.g., Gardner et al., 2022) and interviewed charter-for-hire and commercial fishermen in those areas. We continued interviewing individuals until we reached a saturation state, where little new substantive information was gained from additional interviews. We then proceeded to interview charter-for-hire and commercial fishermen in other regions of the Gulf where red snapper is a smaller percentage of the fishery, to capture any regional differences in perspectives. Finally, a small number of private recreational fishermen were interviewed to ensure that any differences in perspectives among fishing fleets were accounted for. However, the universe of private recreational red snapper fishermen is incredibly vast and diverse, so we did not expect to reasonably encompass all the perspectives from that sector. The local knowledge compiled for this study therefore represents a thorough but not exhaustive collection of the observations and opinions of Gulf red snapper fisheries resource users. Via informal phone conversations, each fisherman was asked to share their experience and perceptions of the Gulf red snapper population and fishery, with the goal to address the following research questions:

1. What are the main factors (environmental or otherwise) that influence the Gulf red snapper fishery and red snapper populations?
2. What do fishermen perceive as the risks in the fishery and what do they value?
3. How do changes in the ecosystem affect businesses and communities?

Interview transcripts were then used to draft a conceptual model encompassing the entire Gulf region (Texas, Louisiana, Mississippi, Alabama, and western Florida). The model was created using the online software platform Kumu (www.kumu.io). All factors and linkages mentioned by fishermen were included in the model based on the interview transcripts. For example, if a recreational fisherman mentioned that they do not go fishing as often when fuel prices are high, we would create two factors, fuel prices and recreational trips. We would draw a linkage (directed arrow) from fuel prices to recreational trips and characterize the relationship between the factors as negative, meaning an increase in the starting factor (fuel prices) would lead to a decrease in the ending factor (recreational trips). Information from each individual fisherman was sequentially added, building the model up from previous interviews. When fishermen mentioned the same linkages between factors, we weighted those linkages by the number of individuals who mentioned them (visualized by the width of the arrows in Kumu). These weights were used to assess aspects of the system of particular interest to a wide range of fishermen. Finally, linkages were added to the model in cases where those linkages were well known (e.g., red snapper recruitment to red snapper abundance) even if they were not explicitly mentioned by fishermen.

Since the model was developed by the authors based on interview transcripts, it was important to ensure that the model accurately portrayed the perceptions of fisheries resource users. We therefore presented a draft version of the model to a subset of commercial, recreational, and charter-for-hire fishermen ($n = 13$) during a workshop held concurrently with a Gulf Council meeting. Workshop participants were walked through the model and asked to revise nodes and connections as needed, until a consensus model was created. The final model was analyzed using the social network analysis methods available within the Kumu platform. Social network analysis is a method for uncovering the dependencies between variables in a network, including how they affect the network as a whole (Tabassum et al., 2018). We analyzed degree centrality, which is simply the number of connections each node has, to determine which factors were the most central to the model.

2.2. *Linking participatory conceptual modeling to stock assessment*

As previously mentioned, the SocioEconomic Aspects in Stock Assessments Workshop (SEASAW) report was used as a general guide for identifying the ways the red snapper participatory conceptual model could inform the red snapper assessment. The report breaks down the stock assessment process into six steps (data collection, data processing, stock assessment models, projections, harvest control rules, and communication with managers and resource users) and suggests how socioeconomic information should be used in each step (Chan et al., 2022). Here, we describe the specific methods identified for linking ecosystem and socioeconomic information to each step using participatory conceptual modeling. In the Results section, we provide examples of each method using the red snapper conceptual model and the most recent Gulf red snapper stock assessment (SEDAR 74; SEDAR, 2024). Although SEDAR 74 is the most recent stock assessment, it was not used for management advice and model projections were not run. In the projections section of the Results we therefore refer to the most recent assessment where projections were run (SEDAR 52; SEDAR, 2018).

Table 1
Steps of the stock assessment process and ways participatory conceptual modeling can contribute socioeconomic and ecosystem information to each step, including the specific methods used in this study. CPUE = catch-per-unit-effort. EBM-DPSER = Ecosystem Based Management Driver, Pressure, State, Ecosystem service, and Response model (Kelble et al., 2013).

Stock assessment step	Benefit of Participatory Conceptual Modeling	Method
Data collection	Identify driving variables in conceptual models to identify data collection needs	Social network analysis and EBM-DPSER categorization
Data processing	Identify factors that should be considered when standardizing CPUE or estimating discard mortality	Identify the in-arrows to CPUE and discard mortality in the model
Stock assessment models	Characterize uncertainty in model parameters and improve parameterization	Examine factors in the model related to stock assessment parameters (e.g., selectivity, retention, recruitment)
Projections	Identify stock and fishery dynamics that may change when running projections	Look at table of dynamics used for projections, see what is in the model, examine transcripts for major changes over time
Communication with managers and stakeholders	Examine potential unintended consequences of management actions and actions to improve angler satisfaction	Examine the out arrows from management actions in the model and examine linkages to nodes related to angler satisfaction

We identified benefits of the approach for each step of the process except for harvest control rules (Table 1). Harvest control rules (HCRs) are pre-defined procedures used to set catch limits and are based on either the current or projected state of a fishery (Punt, 2010). There are numerous forms HCRs can take depending on data availability, scientific uncertainty, and management goals. In the United States, the Magnuson-Stevens Act awards considerable flexibility to the eight Regional Fishery Management Councils in terms of how to develop HCRs that meet the Act's requirements. Control rules are therefore often stock and area specific, and incorporating ecosystem information into them is not entirely straightforward (though see some suggestions in Free et al., 2023). Currently, a constant fishing mortality (F) harvest control rule is used for the Gulf red snapper fishery. Specifically, the acceptable biological catch (ABC) is set at the yield at 75 % F_{MSY} following the methods of (Restrepo et al., 1998). This fixed approach does not allow for any input from other sources. The HCR step of the stock assessment process is therefore not considered in the red snapper case study. However, we provide suggestions for how participatory conceptual modeling could inform HCRs in other situations in the Discussion.

2.2.1. Data collection

The data collection step of the stock assessment process includes fisheries-independent data from biological surveys, fisheries-dependent data on catch and effort trends, biological characteristics of landed and discarded fish, and abiotic and other relevant ecosystem data. Identifying the components of the greater ecosystem and socioeconomic landscape that are important to include in stock assessment models is extremely challenging. While it is well recognized that a myriad of external factors can influence fish stocks and fisheries, there is a lack of standardized methods for determining which of these factors are important to consider in a stock assessment context. Participatory conceptual modeling can help reveal important change agents in the system, and the trickle-down effects that might warrant changes to data collection methods. Using the red snapper case study, we developed a two-step approach for identifying key drivers based on participatory conceptual models. The first step is to use social network analysis to identify the most influential variables in the system. Specifically, we employed a social network method called micmac (matrix cross-reference multiplication applied to a classification). Micmac is a structural analysis method that was originally proposed by Duperrin and Godet (1973), and is used to examine the relationships between variables in a system and discover the key variables. The dependence relationships among all variables are drawn as the influence-dependence (or influence-exposure) chart (Chen, 2018). Micmac was calculated for the red snapper model by a Kumu algorithm developed based on calculations of micmac in the literature (Asan et al., 2004; Diaz, 2013; Linss and Fried, 2010; Serdar Asan and Asan, 2007).

Once micmac influence values were calculated for each node, the second step of our method was to categorize each node in the model according to the Driver-Pressure-State-Ecosystem Services-Response (EBM-DPSER) framework (Kelble et al., 2013). Drivers reflect underlying human needs and desires, while pressures are factors that manifest from system drivers and directly impact the state of a system (i.e., the quantity and quality of biological, physical, and chemical phenomena, including fish abundance). Ecosystem services are benefits people receive from the system, and responses are the actions taken by governments, individuals, or organizations aimed at changing system states and enhancing ecosystem services (Gari et al., 2015; Kelble et al., 2013). Drivers are often high-order system variables and are rarely affected by responses. However, management actions or interventions often can have an impact on pressures. By focusing on pressures that have a high influence on the system (high micmac influence score), we can examine in detail the factors that directly impact the state of the fish population and fishery. Additional data collection may be warranted for some of these pressures if they are not currently considered during stock assessment. Using the red snapper conceptual model, we created an influence-exposure chart using only the nodes labeled as pressures. The pressures with the highest micmac influence scores (>0.8) were highlighted as key system pressures and examined in more detail in the model and transcribed interviews.

2.2.2. Data processing

Once fisheries-independent and dependent data are collected for a stock assessment, the next step is to process the input data. This includes calculating abundance indices from fishery-dependent catch data or fisheries-independent survey data as well as estimating fishery discards. When calculating abundance indices, it is important to account for factors besides fish abundance that may influence catch rates (Maunder and Punt, 2004). Particularly for fisheries-dependent CPUE indices, these factors can be difficult to identify without detailed knowledge of fishery operations and fish behavior. But even with fisheries-independent surveys, there can sometimes be ecosystem drivers that are unaccounted for when estimating fish abundance. Estimating discard mortality is another important component of data processing, as changes in discard mortality over time can affect estimates of total fishery removals. However, direct observations of the mortality of discarded fish are limited and mortality estimates can therefore have high uncertainty. To improve CPUE standardization and estimates of discard mortality in stock assessments, conceptual models can be examined for the in-arrows to CPUE and discard mortality (referred to as post-release mortality in the red snapper model). The nodes connected via in-arrows are all components expected to have some effect on CPUE or discard mortality and therefore should be considered during data processing. If any of the connected nodes are not currently being considered, fishermen's knowledge may be able to provide the information needed to improve data processing. In some cases, the conceptual model may highlight additional data collection needs during this step.

We began by highlighting the red snapper CPUE and post-release mortality (discard mortality) nodes in the Kumu model, as well as the nodes connected to CPUE/post-release mortality via in-arrows (i.e., the elements identified as having a positive or negative impact on CPUE/post-release mortality) within two degrees. This allowed us to capture not only the elements that directly affect data processing nodes, but also the indirect drivers. We then closely examined each of the remaining elements linked to the data processing nodes, and drew insights about their specific impacts from the transcribed interviews.

2.2.3. Stock assessment models

Each stock assessment model estimates a number of parameters relating to fleet behaviors and population processes. To examine how participatory conceptual modeling could inform these parameters, we first examined the different types of parameters estimated in the most recent red snapper stock assessment model (SEDAR, 2024). We then explored which, if any, nodes in the red snapper conceptual model related to each parameter. Model connections were examined to determine which ecosystem and socioeconomic factors may have an impact on some of the most uncertain parameters (focusing on the in-arrows to the parameters of interest). Transcribed interviews were then reviewed for any mentions of specific changes in these factors to aid in parameterizing the red snapper stock assessment model and characterizing uncertainty.

Selectivity refers to the probability of capture by age or length for a given fleet. Multiple interrelated factors dictate selectivity, including gear type, targeting behavior, and availability of fish due to spatial and temporal constraints on fishing effort. Selectivity estimations are a common source of uncertainty in stock assessments because changes in the behavior of fishermen (such as changes in targeting or fishing locations) can be difficult to observe and measure. Retention is another important parameter that describes how fish are landed vs. discarded in targeted fleets. Discarding behavior, specifically why fishermen choose to keep or discard particular fish and how those choices change over time, is difficult to observe and monitor. Retention estimates and estimates of the magnitude of fisheries discards in general therefore also tend to have high uncertainty. In stock assessment models, population processes such as recruitment are often estimated with high uncertainty as they can be influenced by a myriad of unknown ecosystem drivers. For these reasons, nodes and linkages related to selectivity, retention, and recruitment were examined in the red snapper conceptual model. As an attempt to decrease some of the uncertainty associated with these parameters, we illustrate how participatory conceptual models can be used to develop specific hypotheses concerning patterns in stock assessment parameters.

2.2.4. *Projections*

Projections of the fish population from the terminal year of a stock assessment forward in time are used to determine the overfishing limits and allowable biological catch, and to set annual catch limits. Due to the complex nature of stock assessments and data streams in the Southeast region, the terminal year of the assessment is typically a couple years behind the present date. By the time management actually gets implemented the catch advice may be dependent on assumptions that are outdated by several years. When projections are run, all the stock and fishery dynamics are typically based on recent averages from the terminal years of data, which–in an era of rapid change–can potentially be a poor representation of present dynamics. Participatory conceptual modeling allows us to acquire information about changing fishery dynamics in real time from fishermen constantly on the water, potentially helping to bridge the gap between assessment results based on terminal year assumptions and the current state of the fishery.

We first examined the list of stock and fishery dynamics that are derived when running model projections for red snapper (SEDAR, 2024). We then examined which of these dynamics were included in the conceptual model, and of those, which dynamics may change significantly between the terminal year of a red snapper stock assessment and the year management decisions are being made. Once dynamics were identified, the transcribed interviews were examined for additional details about changes over time, and testable hypotheses were formulated.

2.2.5. *Communication with managers and resource users*

The last step in the stock assessment process where socioeconomic information can be better incorporated is communication with managers and resource users. The SEASAW report recommends that socioeconomic data should be used to inform interpretations of advice, uncertainty, and risk. Stock assessment models provide quantitative catch targets and limits, but do not provide any recommendations for how managers should respond. Participatory conceptual models can provide some of the context around stock assessment results that allow fisheries managers to make more informed decisions. Managers have a suite of regulatory actions they can choose from to respond appropriately to assessment model results. However, it can be difficult to determine which regulatory actions will most effectively accomplish management goals with minimal negative repercussions. Fisheries resource users are uniquely situated to observe cause and effect processes and socio-ecological feedback loops, including factors that are typically not measured or accounted for by stock assessment scientists and managers. Participatory conceptual modeling aids in visualizing these processes as reported by resource users, and allows for examination of downstream impacts and unintended consequences of management actions. We examined the red snapper model for any management regulations and highlighted the out arrows (downstream effects) stemming from each regulation as well as secondary effects.

The red snapper conceptual model contained several regulation nodes, including recreational size limit, bag limit, and season length, the number of federal for-hire permits, and IFQ (Individual Fishing Quota) implementation. On the recreational side, decreased bag limits, size limits, and short seasons were used to decrease fishing effort and allow the red snapper population to rebound after the stock collapsed in the 1980s. These efforts achieved the intended results, with the red snapper population rebounding by the mid-2000s (Hood et al., 2007). Since then, bag limits and season length have most commonly been altered in response to changes in red snapper quota, with the goal of maximizing fishing opportunity while ensuring the red snapper population continues rebuilding. On the commercial side, a major management action was a transition to an IFQ fishery in 2007. Using the conceptual model, we examined the perceived positive and negative repercussions of these management actions according to fisheries resource users.

3. Results

3.1. *Participatory conceptual model*

A total of 53 fishermen (52 male and 1 female) were interviewed for this project between 2021 and 2023, representing the charter-for-hire (29 captains), commercial (13 captains) and private recreational (11 fishermen) sectors. The final Gulf model included 95 nodes and 187 linkages (Fig. 1). An interactive version of the model can be found at https://gulf-iea.kumu.io/gom-red-snapper-participatory-model. Recreational fishing effort (recreational trips) was the central hub of the model, with the highest degree centrality (Table 2), suggesting it is the most important component of the red snapper system according to fishermen (though it is important to note that 75 % of interviewees were recreational fishermen). Local abundance of red snapper above the size limit was another important node, and was separate from red snapper Gulf abundance. This suggests that the local dynamics of the red snapper fishery are just as if not more important to fishermen than the dynamics of the entire stock. Other nodes related to the recreational fishery were also central to the model, including CPUE, high-grading and discarding, and season length. The importance of these nodes underscores the influence of human behavior and management actions on the red snapper system. The local economy was a central node, as was commercial lease price, suggesting that fluctuations in the economy may have a substantial impact on the behavior of fishermen. Out of the ecosystem nodes identified in the model, hurricanes were the most central, with several notable impacts on the system. In the sections below, quotes from the interviews with fishermen are referenced to highlight particular observations relevant to each step of the stock assessment process. All quotes can be found in the supplemental material (Table S1).

3.2. *Data collection*

The micmac analysis (Figure S2) and DPSER categorization of the red snapper model revealed 20 key system pressures (Table 3), including a mix of both socioeconomic and ecosystem nodes. We identified 10 potential research priorities associated with these nodes. These included the impacts of hurricanes, water temperature, freshwater flow/turbidity, oil spills, red tide events, underwater pipelines, predators (sharks and dolphins), technological advancements in seafloor mapping, and the COVID-19 pandemic on red snapper populations and fisheries, and the importance of oil rigs as red snapper habitat / fishing grounds. We also identified six data collection priorities, including better estimates of discarding, discard mortality, depredation frequency, the spatial distribution of recreational fishing effort, the number of private recreational fishermen, and illegal or unreported recreational fishing. Several of these pressures are not currently considered in the red snapper stock assessment, and changes over time could therefore bias assessment results.

The transcribed interviews accumulated as part of the participatory conceptual modeling process can provide additional insight into these pressures and how they relate to the red snapper stock assessment. For example, illegal or unreported recreational fishing was identified as a key system pressure, but estimates of illegal catch are not included in the red snapper stock assessment, and unreported or misreported catch can bias the catch estimates. Numerous fishermen linked changes in boat

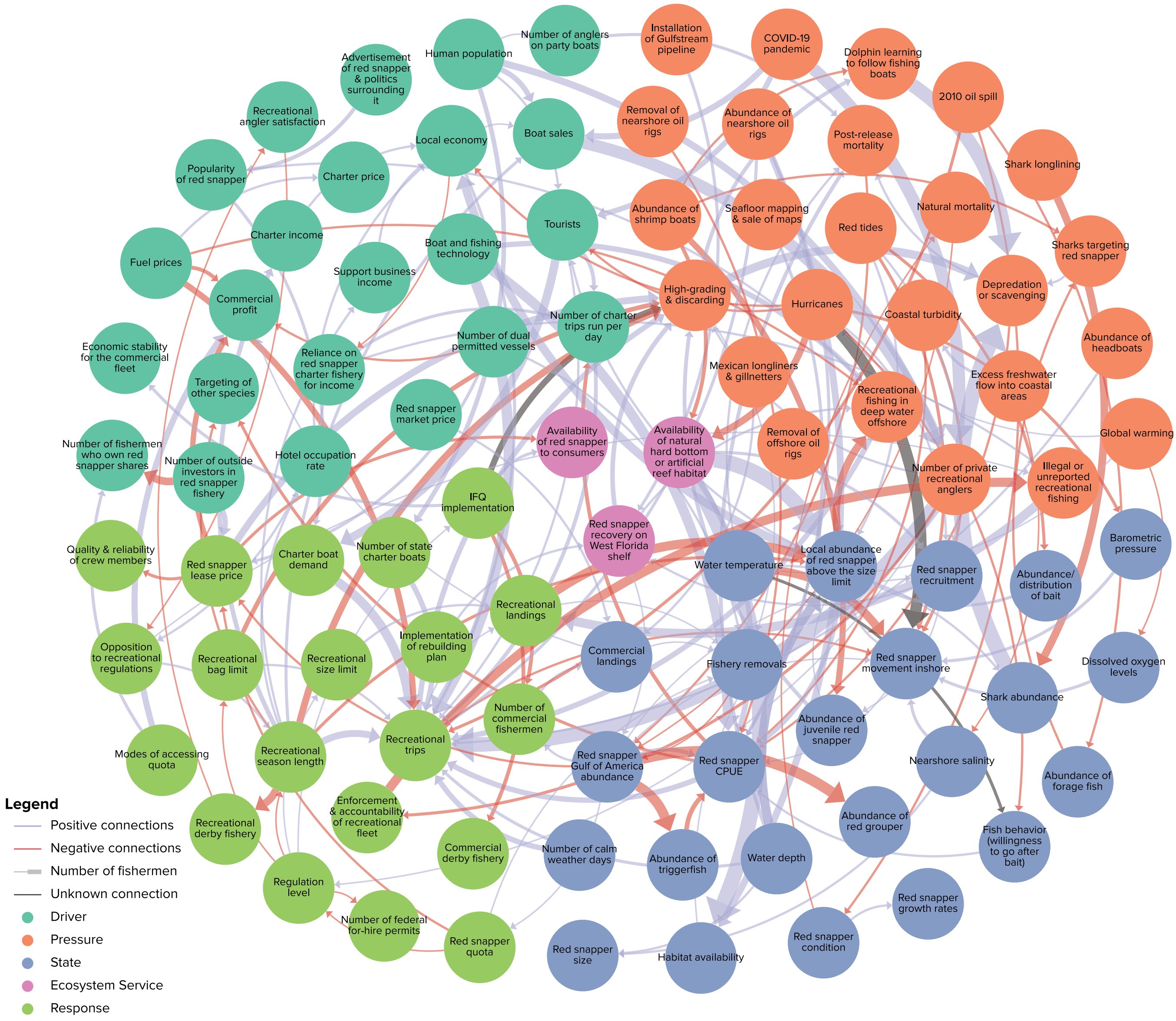

Fig. 1. Participatory conceptual model of the red snapper fishery in the Gulf of America. Nodes are colored based on categorization into the EBM-DPSER framework. Directional arrows are color coded by type of connection (positive, negative, or unknown). The width of the arrows denotes the number of fishermen who mentioned each particular connection. We checked whether this image was friendly to people with moderate-to-severe, red-green colorblindness (deuteranopia) using Brigham Young University's Colorblind Image Tester (Stevens et al. 2024).

Table 2
Top nodes in the Gulf red snapper conceptual model based on degree centrality (degree values greater than or equal to 8).

Node	Degree centrality
Recreational trips	20
Red snapper catch-per-unit-effort	15
Local abundance of red snapper above the size limit	15
Red snapper Gulf of America abundance	12
Red snapper movement inshore	11
Recreational season length	11
High-grading and discarding	11
Red snapper lease price	8
Hurricanes	8
Local economy	8

and fishing technology in recent years to an explosion in recreational fishing effort. These changes have purportedly made it extremely difficult to determine the universe of recreational fishermen and figure out what they are catching, especially when fishermen engage in unexpected behaviors, such as taking vessels made for shallow water fishing into areas far offshore (quote 1). Fishermen also had specific observations about how changes in stock size can affect fisherman behavior in ways that could bias certain reporting programs (quote 2). One fisherman explained that when data are only sparsely collected from a sample of the fishermen population, people may feel less inclined to report, because they don't think the catch and effort estimates are accurate (quote 3). There also appeared to be some temporal changes in perceptions of reporting behavior. Some fishermen mentioned that in the past there was a general distrust of state and federal government entities and/or a lack of awareness about the importance of data collection programs, which led to issues with non-reporting. However, reporting seems to have improved in recent years with a general increased awareness that better accountability benefits both fish populations and fisheries (quotes 4, 5). Nevertheless, some fishermen felt that even if recreational reporting may have improved over time, the information that is being reported and collected is not very accurate and

Table 3
Pressures in the red snapper conceptual model with micmac influence > 0.8, ranked by degree, and potential data collection/research priorities associated with each node. Nodes in bold are described in detail in the text.

Node	Degree	Micmac influence	Data collection / research priority
High-grading & discarding	11	0.92	Better estimates of discarding
Hurricanes	8	0.86	Research impacts of hurricanes on red snapper and habitat
Number of private recreational anglers	7	0.94	Characterize the universe of recreational anglers
Recreational fishing in deep water offshore	**6**	**0.81**	**Estimates of changes in the spatial distribution of recreational effort over time**
Depredation or scavenging	6	0.96	Better estimates of depredation frequency
Illegal or unreported recreational fishing	**4**	**0.86**	**Estimates of misreporting, underreporting, and illegal fishing**
Abundance of shrimp boats	4	0.96	Shrimp boat bycatch is included in the red snapper stock assessment
2010 oil spill	3	0.93	Research impacts of oil spills on red snapper populations and fisheries
Sharks targeting red snapper	3	0.86	Research interactions between sharks and red snapper
Covid pandemic	3	0.85	Research impacts of Covid on fishing effort and distribution
Abundance of nearshore oil rigs	3	0.81	Research the importance of oil rigs as red snapper habitat / fishing grounds
Coastal turbidity	3	0.90	Research impacts of freshwater flow/turbidity on red snapper populations and fisheries
Dolphin learning to follow fishing boats	3	0.86	Research interactions between dolphins and fishing operations
Global warming	3	0.93	Research impacts of water temperature on red snapper populations
Excess freshwater flow into coastal areas	2	0.82	Research impacts of freshwater flow/turbidity on red snapper populations and fisheries
Installation of Gulfstream pipeline	1	0.89	Research on how underwater pipelines impact red snapper populations
Abundance of head boats	1	0.81	Head boat landings are already considered in the stock assessment
Seafloor mapping & sale of maps	1	0.93	Research impacts of technology changes on catchability
Removal of nearshore oil rigs	1	0.93	Research the importance of oil rigs as red snapper habitat / fishing grounds
Removal of offshore oil rigs	1	0.93	Research the importance of oil rigs as red snapper habitat / fishing grounds

shouldn't be trusted to inform changes in the quota (quote 6). Finally, there were numerous observations of unreported illegal harvest, including harvesting more than the legal limit and also fishing across state boundaries (quotes 7, 8, 9).

Recreational fishing in deep water offshore was identified as another key system pressure. While there are extensive time series of recreational landings and discards for Gulf red snapper, these numbers do not give a complete picture of changes in the fishery landscape over time. Red snapper fishermen observed that recreational effort has increased substantially over time, and that fishing technology has made it easier for novice fishermen to target and catch red snapper even in offshore areas. The following quotes from charter captains highlight some of the impacts of this increased effort, including localized depletion that forces fishermen to move further offshore to target red snapper (quotes 10, 11). Advancements in boat and fishing technology have allowed recreational fishermen to target fish in previously unknown or inaccessible areas. Another key system pressure identified in the conceptual model was depredation. Depredation is the complete or partial removal of a hooked fish by a predator before it can be retrieved by a fishing vessel (Mitchell et al., 2018). Increased discarding, increased shark populations, and generational learning by bottlenose dolphins to follow fishing vessels were cited as causes of the increased depredation. Red snapper fishermen had specific observations about changes in both high-grading and discarding in general over time (quotes 12, 13). High-grading is defined as the discarding of legal sized fish either intentionally or due to regulatory limitations. Fishermen have noted that discarded fish tend to attract predators, and that some predators have begun to associate fishing vessels with easy prey, leading to a congregation of predator species on common fishing grounds. Fishermen have observed that an increase in predator encounters have led to increased depredation incidence. The perceived change in depredation over time could have impacts on the red snapper population and fishery that are not currently considered in the data collected for red snapper assessments.

Table 4
Categories of model parameters estimated in the red snapper stock assessment model (SEDAR, 2024) and related nodes in the system dynamics model.

Parameter category	Related nodes in system dynamics model
Fishing mortality	Fishery removals
Stock-recruit deviations	Red snapper recruitment
Stock-recruit relationship	Red snapper recruitment
Recruitment apportionment	Red snapper recruitment
Selectivity	IFQ implementation, Recreational fishing in deep water offshore
Retention	High-grading & discarding
Catchability	Red snapper CPUE
Length/age composition weightings	Red snapper size

3.3. Data processing

3.3.1. CPUE standardization

In the latest red snapper stock assessment (SEDAR, 2024), the stock synthesis model used several abundance indices derived from a variety of both fishery-dependent and -independent data sources. Ensuring these indices are appropriately standardized to account for external variables could lead to improved model fits. Red snapper fishermen identified several factors that could influence catchability of red snapper, and thus impact the accuracy of CPUE data as an index of fish abundance. Not surprisingly, both local and Gulf-wide abundance of red snapper were identified as impacting red snapper CPUE. Since CPUE is used to estimate population abundance in a stock assessment context, the Gulf-wide abundance element was ignored in the focused view of the Kumu model. Based on the red snapper model, localized depletion, changes in fishing technology, abundance of triggerfish, availability of structured habitat (including natural and artificial), coastal turbidity, depredation, and fish behavior (movement inshore and willingness to go after bait) are all factors that may impact catchability (Fig. 2). Analyzing the second-degree connections revealed that hurricanes have an impact on three of these factors; availability of habitat, red snapper movement, and willingness to go after bait. Several fishermen mentioned that hurricanes can dislodge smaller artificial structures, which are the main habitat recreational fishermen target for red snapper in some regions. When the number of structures with known locations declines after a hurricane, it can lead to a decrease in red snapper catchability as fishermen have to move to structures further away or locate new structures (quotes 14, 15). Fishermen also observed that hurricanes can redistribute red snapper biomass and influence the behavior of red snapper (quotes 16, 17, 18, 19). Fishermen specifically noted that right after a

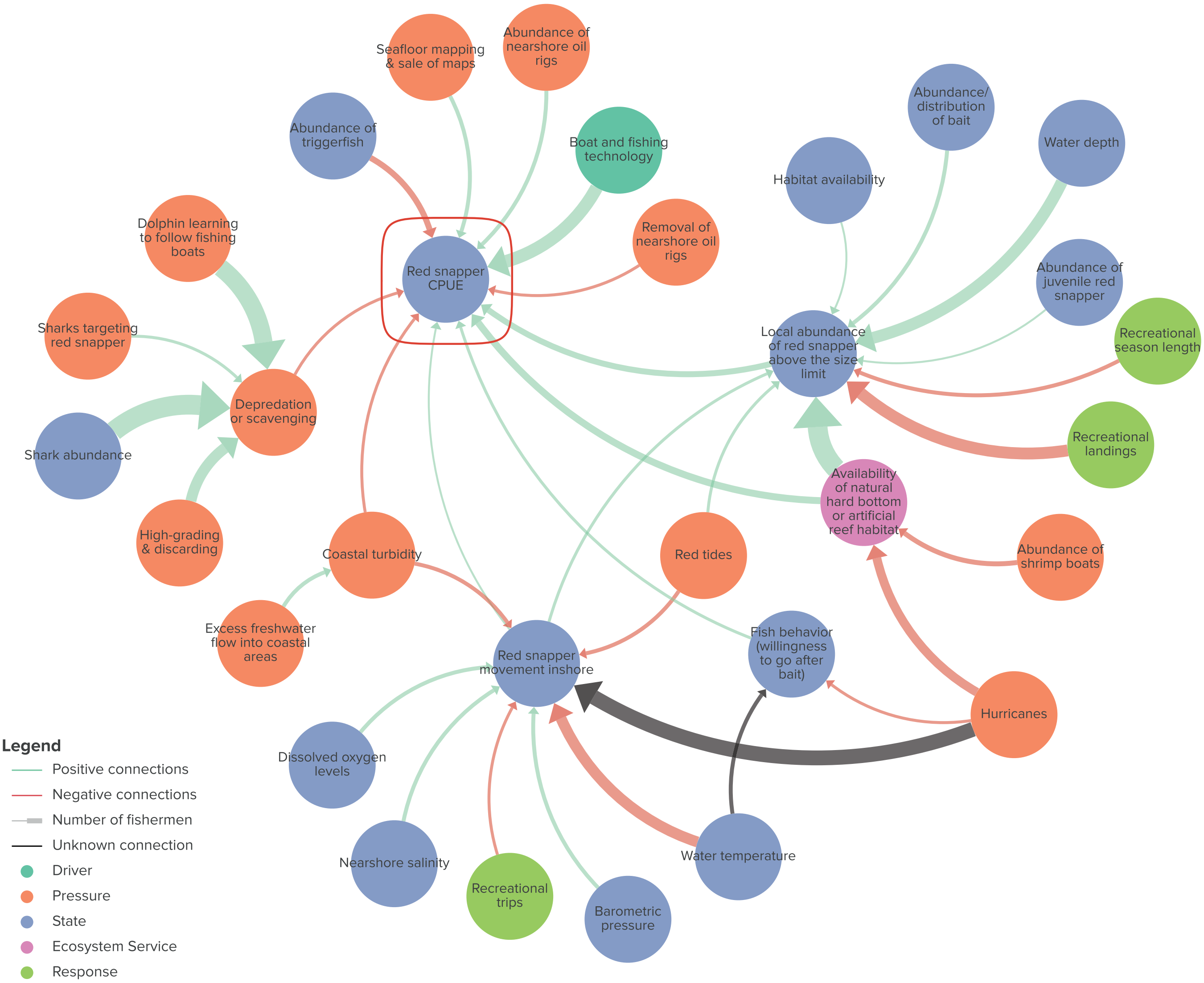

Fig. 2. Subset of the red snapper conceptual model highlighting the red snapper CPUE node, as well as the nodes connected to CPUE via in arrows (i.e., the elements identified as having a positive or negative impact on CPUE) within two degrees.

hurricane red snapper appear hungrier than usual and are more willing to go after bait. Red snapper may move either towards or away from fishing grounds depending on hurricane direction and speed, which may either increase or decrease catchability.

As mentioned previously, artificial reefs have expanded significantly in the central Gulf. Several fishermen noted that the installation of new artificial reefs (especially public reefs) can greatly increase catchability, as the reefs aggregate fish and make it easier for fishermen to target and catch them (quote 20). Another interesting observation was the interaction between red snapper and triggerfish. According to some fishermen, when triggerfish abundance is very high, it can decrease catchability of red snapper. Red snapper tend to reside in the water column below triggerfish, and if triggerfish abundance is too high, it can be difficult to get hooks down past the triggerfish to the red snapper (quote 21). In certain areas of the Gulf, coastal turbidity may also have an impact on catchability. One fisherman observed that when turbidity is exceptionally high due to excess freshwater inflow, it can nearly shut down a fishery for a period of time, as red snapper appear to move away from highly turbid areas (quote 22).

Many fishermen also observed a substantial increase in the number of recreational fishermen targeting red snapper over time, which has led to increased harvest and rapid declines in the local abundance of red snapper close to shore over the course of the red snapper season. Fishermen mentioned that this decline in nearshore abundance leads to a decrease in catchability as the season progresses, since fishermen are required to travel further offshore to target red snapper (quotes 23, 24). Finally, numerous fishermen mentioned that red snapper catchability has greatly increased over time with advances in vessel and fishing technology. Boats are faster and more reliable, which allows recreational fishermen to more quickly and easily access red snapper fishing grounds (quote 25). Fish finder and spot lock technologies have also made it easier to locate aggregations of red snapper and keep boats in place over fishing grounds (quote 26). Technological advancements in GPS and seafloor mapping have also made it easier for fishermen to locate previously unknown structured habitat that may hold red snapper, and have the ability to come back to the same fishing grounds over and over again (quote 27).

3.3.2. *Discard mortality*

Red snapper fishermen observed several factors that they believed affect survival of discarded fish, including fishing depth, water temperature, the density of fishermen on party boats, and depredation (Fig. 3). Many fishermen felt that discard mortality overall was fairly low for red snapper (quote 28). However, some people identified certain

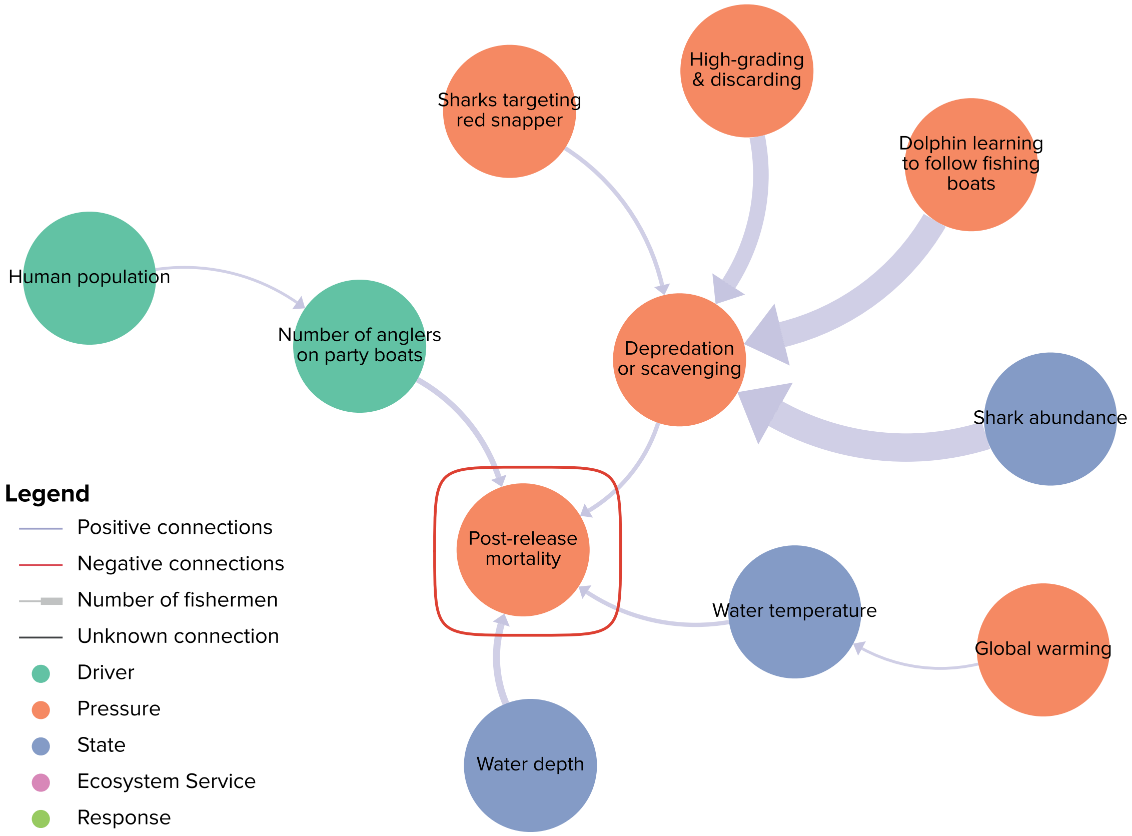

Fig. 3. Subset of the red snapper conceptual model highlighting the post-release mortality (discard mortality) node, as well as the nodes connected to post-release mortality via in arrows (i.e., the elements identified as having a positive or negative impact on post-release mortality) within two degrees.

situations where mortality rates increased substantially. A charter fisherman who operates a large head boat in the central region commented about the negative effects of having the open season in the summer months. According to the fisherman, survival rates for discarded fish are much lower in warmer water than in cooler water. On top of that, there are more tourists in the summer months, so boats are fuller and it is more difficult for deckhands to help passengers release fish in a timely manner (quote 29). Barotrauma was mentioned by a few fishermen, but for the most part it seemed to only be a notable issue in very deep water, especially since descender devices became widely available. If recreational fishermen are fishing further offshore than they used to, barotrauma may be more of an issue than it was in the past (quote 30). As mentioned previously, many fishermen felt that depredation has increased over time. One charter captain in the east region noted a substantial increase in depredation by bottlenose dolphins since about 2010 that he reported has gotten worse every year, and he noted the effects on discard mortality (quote 31).

3.4. *Stock assessment models*

3.4.1. *Selectivity*

In our conceptual model, fishermen identified several drivers that may have resulted in changes to selectivity over time (Fig. 4). These include management changes that have altered targeting behavior, and socioeconomic drivers that affect how accessible certain fishing grounds are to recreational fishermen. The commercial fleet transitioned from a derby-style fishery to an IFQ fishery in 2007, and fishermen reported impacts of this change on where and how they fish. During the derby fishery, commercial fishermen rushed to catch as many fish as possible over a short period of time, often fishing in inclement weather or in areas where they wouldn't normally choose to fish. The institution of an IFQ allowed commercial fishermen to distribute fishing effort over the entire year, and be more selective about when and where they fished and what sizes of fish they targeted. This change in the spatiotemporal distribution of fishing effort due to regulatory change could feasibly have impacted selectivity (quote 32). Similarly, fishermen observed that very short recreational seasons can also lead to a derby-style fishery, while longer seasons may distribute fishing effort and allow fishermen to be more selective about where and when they choose to fish (quote 33).

Fishermen widely mentioned that changes in boat and fishing technology have made it easier for recreational fishermen to target red snapper, and have led to both increased recreational effort as well as increased catchability. Because of this technology, there is the perception that recreational fishermen are fishing further offshore than they used to, encountering larger fish that inhabit deeper waters. One east region charter captain noted that 20 years ago (∼2002) it was much harder for novice fishermen to target red snapper, but technological advancements have made it much easier. An east region recreational fisherman reported an increase in large vessels over the past 15 years (since ∼2007), and a commercial fisherman in the same region similarly noted that dealers have been continually selling bigger and faster boats since 2010. These changes in technology since the mid-2000s may have led to an increase in size selectivity of red snapper by the recreational fleet. On top of the technological advancements, several fishermen noted that localized depletion over the course of the fishing season is a common problem that has been particularly bad in recent years (quote 34). However, fishermen also mentioned that gas prices can dictate how far offshore recreational fishermen are willing to go for red snapper. When gas prices are particularly high, fishermen may run shorter trips closer to shore, where they would be targeting smaller red snapper. There may therefore be some temporal variability in selectivity due to fluctuations in the economy (quote 35).

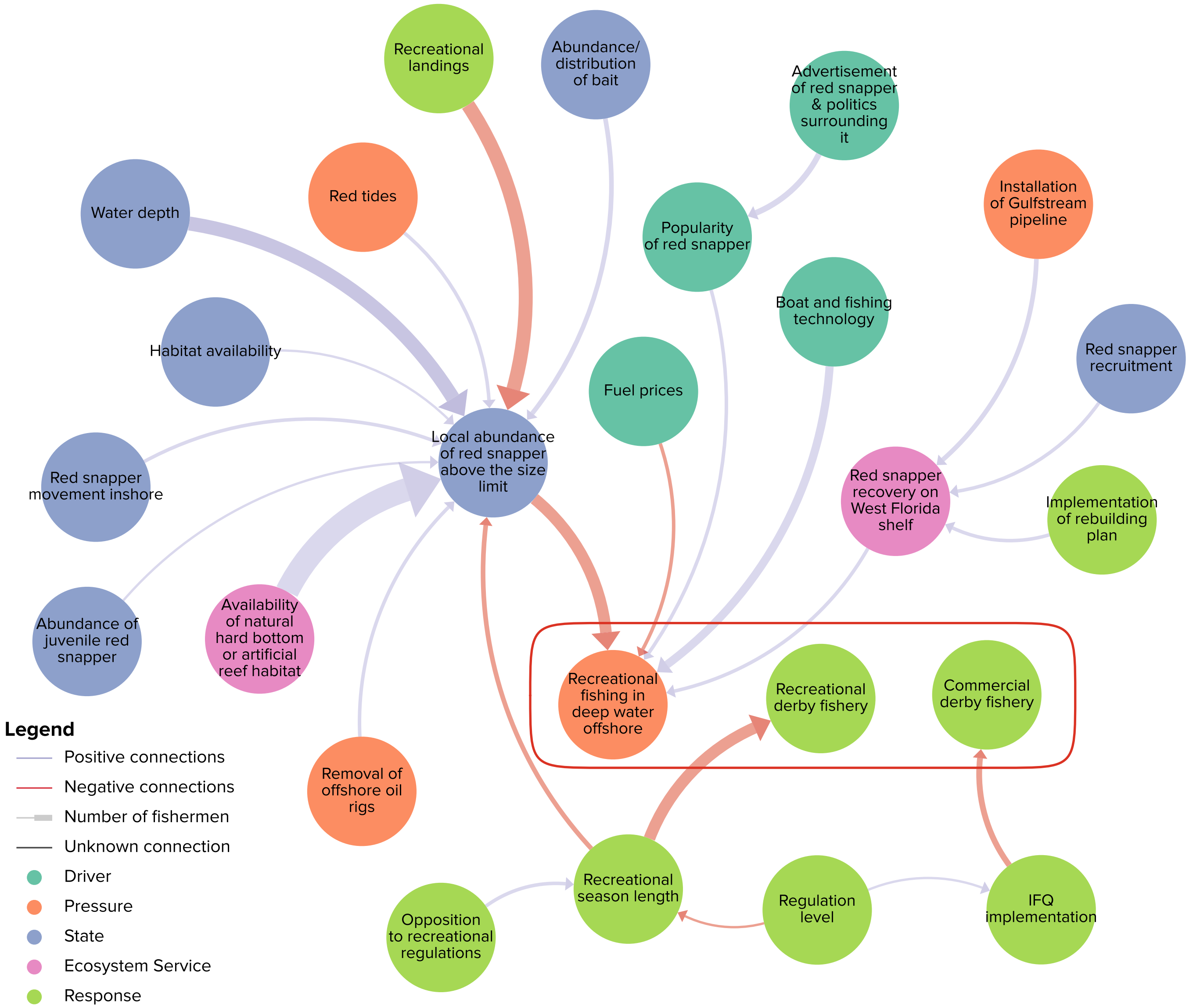

Fig. 4. Subset of the red snapper conceptual model highlighting the nodes related to selectivity (recreational fishing in deep water offshore, recreational derby fishery, commercial derby fishery) and the nodes connected to the selectivity nodes via in arrows (i.e., the elements identified as having a positive or negative impact on selectivity nodes) within two degrees.

3.4.2. *Retention*

Participatory conceptual modeling revealed several factors that fishermen felt impacted discarding behavior, and fishermen described how these factors have changed over time (Fig. 5). Many fishermen reported that the amount of recreational discarding in general has increased due to a variety of factors. There has been a perceived increase in the number of recreational fishermen targeting red snapper over time, due to human population growth, technological advancements that have made targeting red snapper easier, and recently the COVID-19 pandemic. This increased recreational effort is thought to have led to increased discarding. Several fishermen also noted that the institution of a red snapper season greatly increased levels of discarding, since red snapper are often caught incidentally when other species are being targeted during the red snapper closed season (quotes 36, 37).

High-grading was one factor mentioned by both commercial and recreational fishermen. In the recreational fishery, several fishermen noted that because the bag limit is only two fish per person, it encourages high-grading by inexperienced fishermen in particular, who want to retain the largest fish they can find. These fishermen will therefore discard previously caught red snapper above the size limit if a larger red snapper is encountered and landed during a fishing trip (quotes 38, 39). One central region recreational fisherman gave an account of his own discarding behavior, specifically noting how legal or barely legal red snapper are often caught while targeting other species, but these barely legal fish are less desirable and so are discarded (quote 40). It is likely that discarding of legal-sized fish increased once the bag limit was reduced to two fish per person. There was also a previous reduction in the bag limit in 1995, to five fish per person. According to one central region recreational fisherman, this management change likely did not cause increased high-grading, because the abundance of red snapper was so low the average fisherman had a hard time even reaching the five fish per person limit (quote 41).

On the commercial side, the institution of an IFQ fishery had both a positive and negative effect on retention according to fishermen. Commercial fishermen noted that the switch from a derby-style fishery to an IFQ generally decreased discards overall (of all sizes), because there was less of a rush to fish (quote 42). However, the allocation structure of the IFQ fishery (specifically quota leasing) was thought by fishermen throughout the Gulf to cause increased discarding of legal-sized fish. If commercial fishermen catch more red snapper than they have available

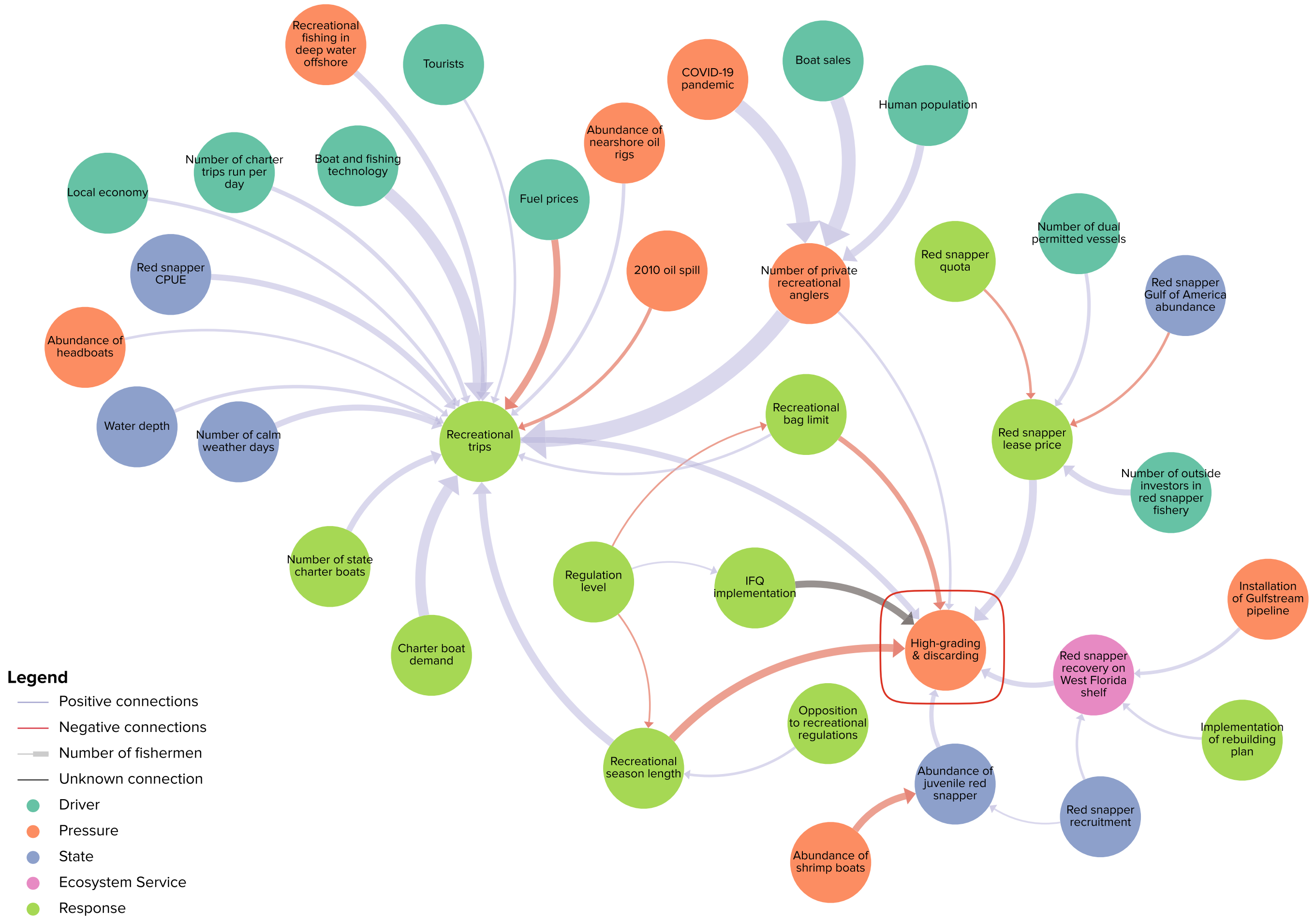

Fig. 5. Subset of the red snapper conceptual model highlighting the node related to retention (high-grading & discarding) and the nodes connected to the retention node via in arrows (i.e., the elements identified as having a positive or negative impact on discarding) within two degrees.

quota, those excess fish must be discarded. High lease prices make it difficult for some commercial fishermen to lease enough red snapper quota to account for fish that are caught while targeting other species (e. g., red grouper). Regulatory discarding was thought to be particularly prevalent in the eastern Gulf (mainly of the west coast of Florida), since commercial fishermen in that region received little red snapper allocation when the IFQ was implemented (quotes 43, 44). High levels of high-grading and discarding in both the recreational and commercial fisheries among other factors were thought to have led to increased scavenging and depredation. High incidence of depredation could feasibly affect retention rates, influencing the size of discards. Fishermen reported having to "discard" fish that would otherwise have been landed and retained due to predators removing often large chunks of fish from hooks before they could be landed whole (quote 45).

3.4.3. *Recruitment*

Although red snapper fishermen did not specifically refer to recruitment as it is defined in a stock assessment context, they did have several observations of ecosystem drivers that might impact settlement or colonization of new recruits (Fig. 6). Specific ecosystem drivers included installations of artificial reefs, hurricanes, and red tide events. One central region charter captain explained his observations of how new artificial reefs become entire ecosystems and potentially create new settlement areas for red snapper recruits (quote 46).

Hurricanes were observed to have varying impacts on red snapper populations and fisheries. One charter captain from the central region noted that large recruitment events appeared to be tied to active hurricane seasons, but he was not sure why (quote 47). Strong hurricane seasons may have some effect on red snapper recruitment, but the direction and intensity of individual hurricanes may also be important. One central region charter captain observed that while smaller hurricanes may benefit fisheries, large, powerful hurricanes may have a negative impact on fish populations (quote 48). In August 2014, a massive red tide event occurred off the Big Bend region on the West Florida Shelf. According to one fisherman, the red tide caused substantial red grouper mortality, which allowed red snapper to recruit into and occupy reefs in more shallow waters than they were typically encountered, where they remained until about 2019 (quote 49). Based on this fisherman's observations, red tide events may benefit red snapper recruitment in instances where the event causes high mortality of species that typically compete with red snapper for habitat and food resources (e.g., red grouper).

3.5. *Projections*

In the latest red snapper assessment model where projections were run (Goethel and Smith, 2018), selectivity for each fishing fleet was assumed not to change over time and was taken from the terminal time block (2016). Discarding practices were also assumed to be the same as the average of the last three assessment years (2013 – 2016). Fisheries resource users reported major changes in recent years in two fisheries dynamics that are used in model projections over time; selectivity (due to changes in where recreational fishermen are fishing) and discard mortality (due to changes in depredation). Especially in regions where access to red snapper habitat (deep water) is further offshore (e.g., central Florida and Mississippi), stakeholders noted that as reliable

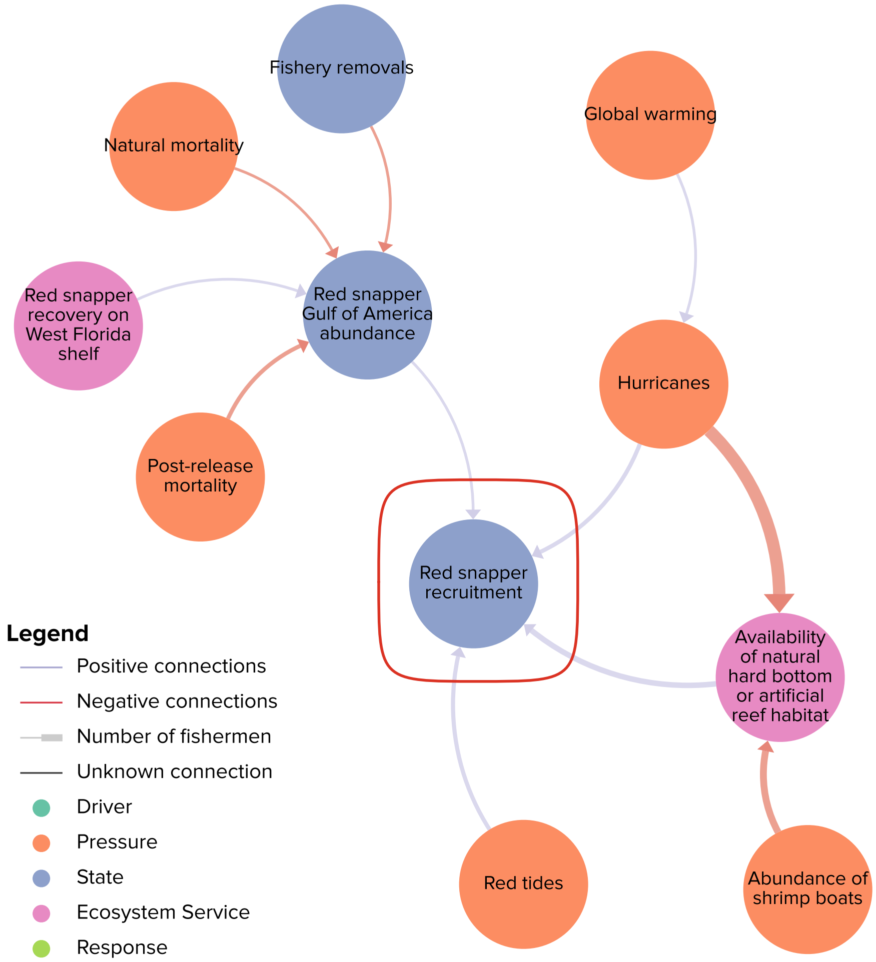

Fig. 6. Subset of the red snapper conceptual model highlighting the red snapper recruitment node and the nodes connected to recruitment via in arrows (i.e., the elements identified as having a positive or negative impact on recruitment) within two degrees.

vessels with larger engines and higher maximum speeds have become readily available to recreational fishermen and guides, it is now easier to access these offshore regions and thus target red snapper than it was in the past. This observation leads to a hypothesis that the recreational fishery is continually moving further offshore. This movement could affect selectivity, retention, and possibly even discard mortality and catchability. Red snapper fishermen also noted a substantial and continuing increase in depredation over time, due to a variety of factors. This increase could lead to a temporal change in discard mortality and possibly retention.

3.6. *Communication with managers and resource users*

The red snapper conceptual model contained several regulation nodes, including recreational size limit, bag limit, and season length, the number of federal for-hire permits, and IFQ implementation (Fig. 7). Several fishermen noted that decreased bag limits, size limits, and short seasons can successfully achieve the management objective of increasing stock abundance (quote 50). However, the conceptual model revealed notable perceived pros and cons to these management approaches. Red snapper fishermen observed that decreases in the bag limit may discourage people from targeting red snapper, since the cost of the trip may not be worth it (quote 51). This change in behavior might appear to achieve the management goal of decreasing recreational effort. However, fishermen also noted an important unintended consequence of small bag limits. Small bag limits may also encourage high-grading, since recreational fishermen are driven to target the largest fish they can find, and may discard smaller legal-sized fish in favor of larger ones (quotes 52, 53). As mentioned previously, increased high-grading and discarding was mentioned as a factor leading to increased depredation, and consequently red snapper discard mortality. Similarly, a decrease in the recreational season length was observed to decrease recreational effort. However, there were numerous additional perceived consequences of short seasons. As with small bag limits, short seasons may lead to increased discarding. According to fishermen, red snapper are often caught incidentally when targeting other reef fish species like triggerfish or red grouper. When the red snapper season is very short, any fish caught outside the season have to be discarded. There were also several perceived socioeconomic ramifications of short seasons, including increased probability of a derby fishery, which decreases fisherman satisfaction. Fishing seasons can sometimes create a “derby” mentality, where fishermen feel pressured to fish on days when they would not normally go fishing (e.g., in inclement weather) because there is only a short window of opportunity to harvest a particular species. Fishermen noted that short seasons, and more specifically seasons that are cut short with little warning, can be especially detrimental to charter captains, local hotels, and support businesses who all depend on tourists coming in for red snapper trips. Above all, most charter captains were in support of more flexible seasons (i.e., allocation-based), or at least set seasons that are scheduled in advance and do not change (quote 54).

The conceptual model revealed several perceived benefits to IFQ implementation, including elimination of the commercial derby fishery, increased economic stability for the commercial fleet, and greater and more consistent availability of red snapper to consumers. It also led to

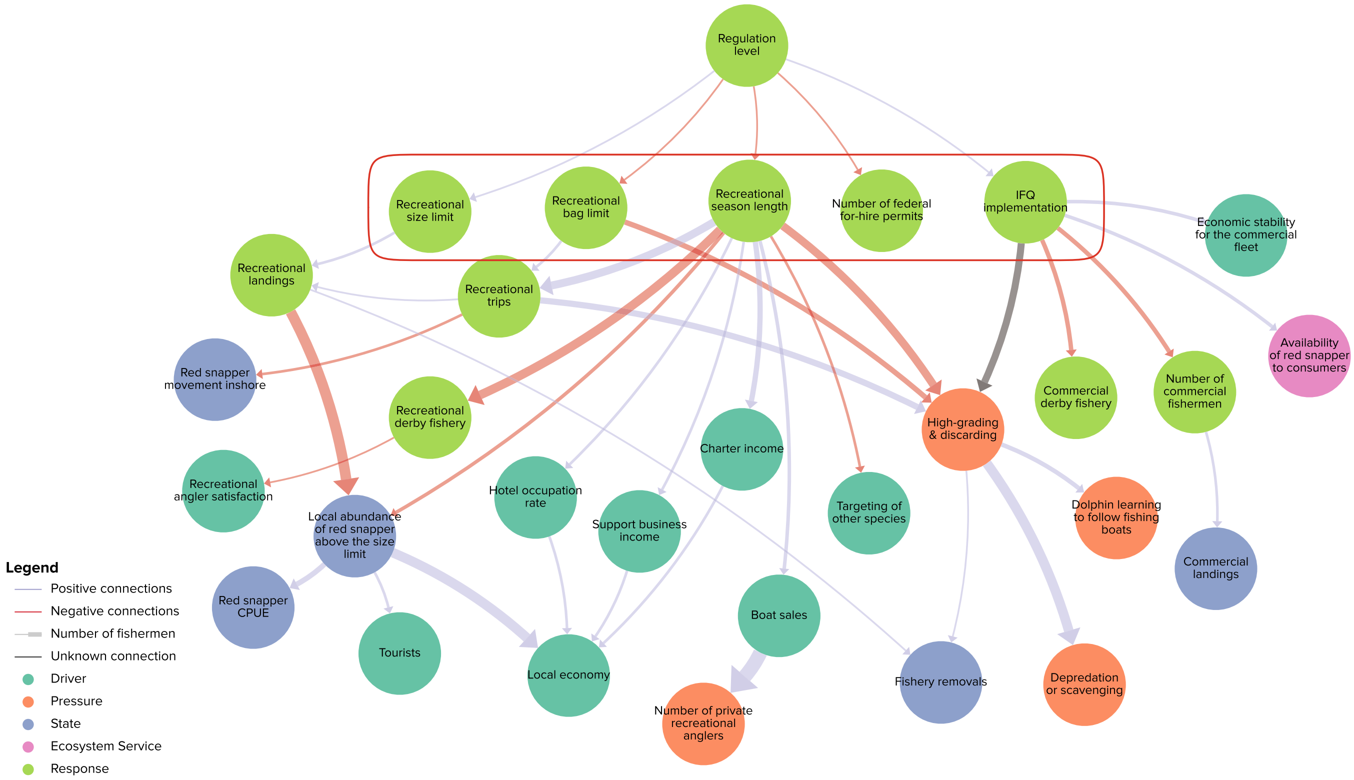

Fig. 7. Subset of the red snapper conceptual model highlighting management actions, as well as the nodes connected to management actions via out arrows (i.e., the identified downstream impacts of management actions) within two degrees.

some consolidation of the fishery, which could either be a pro or con depending on management goals. However, like with the recreational fishery, discarding was also a perceived issue in the commercial fishery. In the conceptual model, the connection between IFQ implementation and high-grading & discarding is labeled as unknown. This is because while many commercial fishermen, especially in the western Gulf, have observed a decrease in discarding since red snapper became an IFQ fishery, other fishermen, particularly in the eastern Gulf, have observed an increase. The individuals reported that when red snapper became an IFQ fishery, with allocations based on historical landings, eastern Gulf fishermen received few shares compared to fishermen in the western Gulf. This was due to historically low abundances of red snapper along the West Florida Shelf. However, in recent years the population has recovered substantially, such that commercial fishermen regularly encounter more red snapper than harvest allocation allows. This has led commercial fishermen to alter their behaviors in a variety of ways. Several commercial fishermen have been forced to purchase more red snapper shares or lease quota if available. But when shares are unavailable or unaffordable, fishermen are forced to avoid known red snapper fishing grounds or discard landed red snapper, often with high mortality rates. Lease prices were linked to discarding in the conceptual models, with high lease prices causing higher discard rates. Fishermen noted that reducing red snapper lease prices in the commercial fishery could therefore help reduce dead discards. A suggested strategy for doing so was to decrease the number of outside investors in the commercial fishery (quote 55).

4. Discussion

4.1. Benefits to the stock assessment process

Through our participatory conceptual modeling exercise, we discovered that the resulting red snapper conceptual model and the underlying information in interview transcripts were ideally suited for incorporating socioeconomic and ecosystem information into the stock assessment process. First, by using the model to elucidate key system pressures, we were able to identify several specific research priorities and data collection needs. Previous research has shown that participatory conceptual modeling and LEK in general can be an excellent tool for identifying knowledge gaps and research priorities, and developing hypotheses about important fisheries systems (Bélisle et al., 2018; Nunes et al., 2019; Röckmann et al., 2012; Seara et al., 2024; Silvano and Begossi, 2010). Our two-step method of applying social network analysis followed by EBM-DPSER categorization to the nodes in a conceptual model provides a standardized way to hone in on the factors within a fisheries system that are major pressures and should be considered when developing stock assessments. This simple approach can help researchers and assessment scientists focus funding and effort towards the ecosystem and socioeconomic processes likely to have the greatest impact on important fisheries. However, everything identified in participatory conceptual models as a key system pressure will not necessarily impact estimates of stock status or management reference points. As a next step, model sensitivity tests could be run to examine potential impacts of considering some of these variables on assessment model results. This practice could help further prioritize data collection and consideration of external variables in stock assessment models.

Fisheries-dependent data on catch and effort trends over time are particularly vital for stock assessments. However, raw CPUE from these data sources is generally not proportional to stock abundance (Harley et al., 2001; Maunder et al., 2006). Understanding the decisions fishermen make when targeting fish species is critical to appropriately standardizing CPUE-derived abundance indices. For example, there are known issues with using CPUE as an index of abundance in tropical tuna purse seine fisheries, largely due to increases in fishing power over time that have been difficult to characterize (Fonteneau et al., 1999; Gaertner and Dreyfus-Leon, 2004). Red snapper fishermen observed a similar technological advancement in the recreational fishery that may be impacting CPUE. Localized depletion was also identified as a major issue in the red snapper fishery. Fishermen might maintain their catch rates or fill bag limits by moving further offshore or improving their bottom-finder technology, which would lead to hyperstability in a CPUE index. Fisheries-dependent data is also generally collected via voluntary or mandatory self-reporting. Numerous factors may influence reporting rates and the validity of such data. In our study, several fishermen believed that some state reporting methods are better and more accurate than others. Fishermen's observations could be used to help determine which particular methods are working well and are likely to collect the most accurate and representative data. Red snapper fishermen also provided detailed information about spatiotemporal heterogeneity in reporting and illegal fishing activity that is not currently considered in red snapper stock assessments. As continued efforts are put into improving data collection in the region, considering these nuances in human behavior could aid in improving catch estimates and abundance indices.

One powerful benefit of participatory conceptual modeling is the ability to formulate testable hypotheses about fishery and population dynamics from model linkages. For example, red snapper fishermen observed that red tides may benefit red snapper recruitment due to a competitive interaction with red grouper. This hypothesis aligns with results from the red snapper stock assessment model. Estimated log recruitment deviations from the 2023 assessment show an interesting and previously unexplained pattern (SEDAR, 2024). Immediately following three major red tide events where substantial red grouper mortality occurred, the log recruitment deviations increased (Figure S2). This observation might be explained by recruitment of red snapper into areas cleared out by red tides.

Red snapper fishermen have also observed significant changes over time in the recreational fishery, primarily due to advancements in boat and fishing technology and increased numbers of recreational fishermen. These observations give rise to questions about where recreational landings are coming from and a hypothesis that recreational fishermen are changing where and how they target red snapper. Existing data may support this hypothesis. The National Marine Manufacturers Association U.S. Recreational Boating Statistical Abstract provides data on outboard engine sales trends (NMMA, 2024). According to the data in the report, while sales of boats in Gulf states with small engine sizes have remained relatively constant over time, sales for boats with 300 + hp engines have more than quadrupled, from only 5432 units sold in 2013–22,520 units sold in 2023, a 314.6 % increase (Figure S3). These changes over time in the recreational fleet suggest that more data on the spatial distribution of fishing effort may need to be collected. This is particularly relevant in light of the results of the Great Red Snapper Count (GRSC), a $12 million USD effort to estimate absolute abundance of red snapper in the Gulf (Stunz et al., 2021). This effort identified a surprisingly substantial biomass in offshore, uncharacterized bottom habitats (Scyphers et al., 2021). However, it is uncertain whether fishermen are willing or able to access those fish (Vaz et al., 2025). Concerns about fuel costs and the time it takes to fish far offshore suggest that the available biomass in offshore habitats may be largely unexploited. This could change, however, if localized depletion continues to be a major issue and improved boat technology continues to make it easier to access those areas. In recent years, red snapper catch limit decisions have been dependent on assumptions regarding the ability of fisheries to target these offshore fishing areas (Gardner et al., 2022). Accurate understanding of where fishermen are willing and able to target specific fish species can help ensure catch limits reflect the actual availability of fish to fishermen, which may differ from the full spatial distribution of fish populations.

Similarly, red snapper fishermen noted a major change in depredation rates over time. Discard mortality is considered in most stock assessments. However, depredation is typically not considered as a component of discard mortality, since depredated fish are not actually landed by fishermen. There is limited data regarding the frequency of depredation in the red snapper fishery, though efforts are currently underway to examine depredation data from fisheries-independent survey data (W.B. Driggers, pers. comm.) The only standardized method of data collection of depredation on fishing vessels is from NOAA observers within commercial fisheries (NOAA Fisheries, 2023). As such, depredation is a source of cryptic mortality within commercial and recreational fisheries, meaning that its contribution to fish mortality is not considered within stock assessments. A workshop specifically aimed at characterizing depredation in the Gulf reef fish fishery was held in 2022 in Gulf Shores, AL (Drymon et al., 2022). During the workshop, charter-for-hire captains were asked to draw trendlines of depredation beginning in the first year they began working. These drawings were used to develop a time series plot that aligns with observations of increasing depredation by fishermen in this study. Preliminary analysis of depredation from fisheries-independent survey data also show an increasing trend over time (W.B. Driggers, pers. comm.). Increased collection of data on depredation frequency and inclusion of depredation as a component of fishing mortality are therefore important priorities for red snapper. Examining external data sources to test hypotheses developed during participatory conceptual modeling can bolster fishermen's observations and provide quantitative information for inclusion in stock assessment models (e.g., Gervasi et al., 2023a).

Another major benefit of developing participatory conceptual models is that they allow for visualization of all the factors identified by fishermen to impact specific processes that are estimated with stock assessment models. For both the data processing and stock assessment modeling steps, examining the in-arrows to important parameters (CPUE, discard mortality, selectivity, retention, recruitment, etc.) allows for rapid identification of factors that are not currently being considered or need to be examined in more detail. The red snapper model highlighted several important components of the ecosystem (depredation, technology, fuel prices, hurricanes, etc.) that may have major impacts on the red snapper population and fishery but are currently not being considered in a stock assessment context. Major changes in these factors over time may warrant their inclusion in data processing and/or model parameterization. For example, a recent acoustic telemetry study revealed that while Gulf red snapper have high site fidelity, increased emigration rates are associated with storms (Lowerre-Barbieri et al., 2025). This aligns with stakeholder observations that hurricanes can impact movement and distribution of red snapper. Since hurricanes are anticipated to increase in frequency and intensity in the Gulf (Liu and Pang, 2013), future research on the impacts of hurricanes on catchability of red snapper is a clear priority. Changes over time in the abundance of artificial reefs and in fishing technology may also need to be considered during CPUE standardization. Species interactions, such as the aforementioned interaction between red snapper and triggerfish on reef habitats, are not often considered when standardizing CPUE, but may be important. Conversation transcripts provided additional details on how these factors impact the red snapper population and fisheries, providing needed context for assessment scientists.

We are currently in an era of rapid global change, in both the climate and in other anthropogenic and biological dimensions (Forster et al., 2023; Halpern et al., 2015). For this reason, the gaps between the terminal years of stock assessment models and when management decisions are being made are becoming more and more problematic. Using catch advice from projections based on outdated assumptions may increase the potential for over- or under-harvesting a stock, and lead to discontent among fishing groups when management decisions based on assessment models do not align with on-the-water observations (Dean et al., 2023). Because data collection, cleaning, and processing take time, the terminal year of a stock assessment is typically about two years behind the present date. As a result, there is always some sort of lag between the terminal year of the assessment and the present day. The initial projection years following the terminal year often represent the current year and can strongly influence catch advice. Participatory conceptual models can help ensure that projections from the terminal year to the present align with anglers' observations. According to red snapper fishermen, selectivity and discard mortality may be changing rapidly enough that model projections used for management advice are outdated. Assessment scientists may wish to examine the impacts of using alternative values for some of these projected parameters, or even consider time-varying parameters if possible. In the Gulf, the LEK of fishermen was previously used to inform stock assessment model projections for red grouper (*Epinephelus morio*) as they related to a large red tide event that occurred after the terminal year of the latest assessment (Sagarese et al., 2021). Fishermen observed a significant increase in natural mortality of red grouper due to the 2017–2018 red tide, but the assessment model terminated in 2017, before the impacts of the red tide event on the red grouper population were evident. Model projections for 2018 that did not include this change in natural mortality provided results that were at odds with fishing industry perceptions of major stock depletion. Our red snapper model highlighted potentially significant changes in recreational fishery selectivity and discard mortality over time that may need to be considered when running model projections. Examining whether projections reflect the observations of fishermen can provide confidence in the results or identify potential issues with the model projections that need to be reexamined.

As mentioned previously, the current harvest control rule that is used for the Gulf red snapper fishery is based on a constant fishing mortality control rule and does not allow for direct input from fishermen. However, there are HCR procedures used in other regions for other fisheries that are flexible and may benefit from information contained in participatory conceptual models. For example, in the SEASAW report it is suggested that socioeconomic metrics could help inform determination of the acceptable risk of overfishing, a metric used by several councils to make management decisions (Restrepo et al., 1998). Risk thresholds are used to set catch limits (like the ABC) and other management measures, and help to buffer against uncertainty. In order to set these thresholds, it is important to understand how much uncertainty there is. Unfortunately, it is very difficult to estimate uncertainty with a stock assessment model. Research has shown that assessment models routinely underestimate uncertainty, since many uncertain parameters have to be fixed either due to data limitations or other reasons (Ralston et al., 2011). Where risk thresholds are used as part of an HCR procedure, fishermen's knowledge may be beneficial, since fishermen's observations often capture nuanced information about subtle changes in the ecosystem that may not be reflected in scientific data (Röckmann et al., 2012). The Southeast Fisheries Science Center is engaged in ongoing simulation work to test various HCRs using a management strategy evaluation (MSE) approach. In this context, participatory conceptual modeling could help to clearly define management objectives–which describe what stakeholders want to get out of the fishery and include legal mandated objectives specified in the Magnuson-Stevens Act. Outlining management objectives allows researchers to be able to quantify optimum yield. Participatory conceptual modeling can help to define HCRs that balance management objectives.

The final step of the stock assessment process is communication with managers and fishermen. Assessment models give a status determination with regard to overfishing thresholds and produce catch quota advice for keeping fishing mortality at a sustainable level, but models do not provide information on what set of interventions is most ideal for constraining mortality at that level. Managers have a variety of choices (e.g., input controls, output controls) when deciding how to achieve stakeholder objectives while ensuring harvest levels remain below the overfishing limits. At this step of the process, participatory conceptual modeling can provide valuable context that can help managers decide how to respond to changes in stock status or overfishing limits derived from stock assessment models. Conservation interventions have historically been made without much evidence that they would achieve the desired outcomes (Pullin et al., 2004; Pullin and Knight, 2003; Sutherland et al., 2004). Furthermore, actions often have consequences that are not considered ahead of time, mainly due to a lack of knowledge about what those consequences might be (Degnbol and McCay, 2007). Many veteran fisheries resource users have observed numerous management changes over the years and are uniquely situated to report on the cascading impacts of those actions. Presenting fishermen's knowledge in a conceptual model provides a clear, easy to follow picture of the outcomes and consequences stemming from management actions. For example, the red snapper model showed that a major change to the commercial fishery (the institution of an IFQ system) provided numerous observable benefits to the fishery and fish population. However, quota was initially distributed based on catch history (which was low in the eastern Gulf due to a lack of red snapper), and managers at the time did not consider that the red snapper population may rebound in the eastern Gulf. Currently, there is a perception among commercial fishermen that there is not enough quota amongst eastern Gulf fishermen to account for the increased red snapper population, which has financial implications (fishermen must pay high lease prices) as well as ecological implications (regulatory discarding). Similarly, short red snapper seasons were perceived to successfully decrease recreational fishing mortality, but may also have unintended consequences, like increased targeting of other recreational species. This highlights the need to consider reef fisheries holistically when making management decisions. Participatory conceptual modeling can help to characterize how fishermen alter their behavior following changes in management. The consequences and feedback loops identified by conceptual models can help managers make more informed decisions about future actions and possibly prevent negative ramifications.

4.2. Limitations

Due to the diverse nature of the recreational red snapper fishery, it was difficult to determine how representative our sample of fishermen was of the true population. It is therefore possible that some important drivers and linkages were missed when creating our conceptual model. However, we identified fishermen to include in this study via multiple entry points in an attempt to gather a range of perspectives from all fishermen involved in the fishery. By interviewing individuals over the phone, we were also able to include the perspectives of individuals who might not otherwise be able to participate in a traditional participatory modeling workshop. We additionally continued interviewing fishermen until we reached a saturation state, where no new information was being added to the conceptual model with additional interviews. This is a common technique used in the human dimensions literature for determining appropriate sample size (Guest et al., 2006). We therefore felt that although our sample may not reflect the full population of red snapper fishermen, our conceptual model is a good representation of the fishery system as perceived by resource users. However, we also caveat that our model is based solely on the perceptions of commercial, recreational, and charter-for-hire resource users. The model may have been different had we included the perceptions of fishery biologists, managers, or other ocean sector users. Stock assessment decisions regarding data collection, data processing, model form and parameterization, and projections are primarily made by scientists, with regular input from management council members, advisory panels (which include fishermen), and members of the public. Attempts are generally made to make the process as transparent as possible. The Southeast Data, Assessment, and Review (SEDAR) process, which is the cooperative process by which stock assessments are conducted in the region, has formally appointed panel members who are resource users. There are also opportunities for the general public to listen in and comment during every Gulf Council Scientific and Statistical Committee (SSC) meeting and to participate in assessment workshops. However, public participation in the stock assessment process is typically limited to a small percentage of individuals who may not represent the full diversity of resource users. Furthermore, there is currently no standard process or procedure for incorporating public comment into the assessment process. As previously mentioned, most fishermen have a depth of knowledge of the specific areas where they fish, but often do not have a breadth of knowledge of fish stocks as a whole. Place-based conceptual modeling is a tool that can be used to coalesce local knowledge into a stock-wide whole. Beyond just considering fishermen's knowledge (i.e., through public comment and inclusion of a handful of resource users on scientific panels) a structured knowledge production approach like the participatory conceptual modeling outlined in this study, provides a more holistic view of fisheries from the lens of resource users. The results of the research outlined in this manuscript allow scientists and managers to harness these perspectives and gain important information that may not already be considered in stock assessments.

Due to travel restrictions surrounding the COVID-19 pandemic, we were limited to eliciting mental models via indirect methods. Indirect elicitation methods involve an analyst using textual information (e.g., interview transcripts) to determine the structure of each fisher's mental models (Carley and Palmquist, 1992; Masinde et al., 2018; Verkerk et al., 2017). Direct elicitation, in comparison, involves fishermen creating and defining their own mental models, typically as a group in a participatory workshop setting (McPherson et al., 2022; Özesmi and Özesmi, 2004). Direct elicitation is more common because it involves the fishermen in the modeling process, provides immediate results, and does not rely on the interpretation of an analyst (Abel et al., 1998; Jones et al., 2011). However, research has shown that indirect elicitation may actually result in less information loss and oversimplification than direct elicitation methods, which are prone to time restraints and participant fatigue (LaMere et al., 2020). With indirect elicitation, an analyst has time to carefully consider and define all model components. However, this method is susceptible to potential bias from the analyst when interpreting the models. We attempted to alleviate this concern by showing the draft model to a small subset of fishermen and getting feedback on the identified nodes and linkages. LaMere et al. (2020) suggests that combining direct and indirect elicitation methods is the best approach to obtain the benefits of each while minimizing the shortcomings. The Rich Elicitation Method (REM) is a multi-step process that begins with direct elicitation via resource user workshops, then moves to indirect elicitation using workshop audio recordings and survey responses to fill in any gaps in the models. Finally, elicited models are sent back to participants for verification. Future studies using participatory conceptual modeling may consider using the REM approach to ensure elicited mental models are truly reflective of the stakeholder's perceptions.

4.3. Future directions

Fisheries are incredibly complex systems, and as such they are notoriously difficult to understand and model. Recent research has recognized the benefits of conceptual modeling in a stock assessment context, and suggested conceptual models be incorporated into the modeling process (La Peyre et al., 2024; Maunder, 2024; Minte-Vera et al., 2024). Conceptual models in general have numerous advantages (many of which are outlined in Minte-Vera et al., 2024). Engaging fisheries resource users in participatory conceptual modeling has additional advantages, including improved communication and engagement with scientists and managers. Involving resource users more explicitly in assessment and management can help to increase their understanding of the process, improve buy-in to management actions, and increase information flow among stakeholders, scientists, and managers (Addison et al., 2013). Resource users are also uniquely situated to observe changes in the ecosystem that may not yet be reflected in scientific data. They can therefore help determine when rapid management interventions may be needed.

Once conceptual models are created and analyzed following the protocols outlined in this study, they could then be used to develop hypotheses about how the system might change in the future. For example, fishermen observed several linkages between climate drivers and red snapper population dynamics / socioeconomic factors. These linkages could be used to develop hypotheses about how the fisheries system might change in the future under different climate change projections, including cascading impacts and feedback loops. Conceptual models can also be used as a starting point for creating results chains that use Fishery Management Plan (FMP) objectives as targets and identify possible strategies to reach those targets. FMPs are designed to explicitly consider social and economic factors that influence and are affected by fisheries. However, more effort needs to be made to move beyond merely describing FMP objectives and actually implementing them in management (Benson and Stephenson, 2018). Results chains provide a succinct, clear way to communicate the various linkages and feedback loops between a management action and some desired outcome (Foundations of Success, 2009; Margoluis et al., 2013). Furthermore, results chains serve as a framework for explicitly considering assumptions and evaluating the likely effectiveness of management strategies (Margoluis et al., 2013). Follow up workshops with fishermen and managers to examine conceptual models and create results chains could help visualize potential actions that may help achieve certain FMP objectives.

As previously mentioned, we aimed to inform the conceptual model generated for the Gulf red snapper fishery in this study using only the perceptions of red snapper fishermen. This enabled us to examine how the perceptions of resource users may differ from existing scientific knowledge, identify knowledge gaps, and understand the interests and needs of the fishing communities. To further improve the incorporation of ecosystem and socioeconomic information into the stock assessment process, our conceptual model could be expanded to include findings from the scientific literature, as well as the perspectives of scientists, managers, and other ocean research users. At the very least, consulting the scientific literature and scientific community could aid in better describing the mechanistic linkages between some of the drivers stakeholders identified and red snapper population / fishery dynamics. Conceptual models are commonly used to inform Ecosystem Status Reports (ESRs) and Ecosystem and Socioeconomic Profiles (ESPs). Using the conceptual model to help inform an ESP for the red snapper fishery could be an additional next step.

5. Conclusion

Link (2018) states that a paradigm shift may be needed for the discipline of fisheries science that involves moving away from a reductionist approach that isolates and attempts to understand each component fish stock and towards a more holistic approach that considers the interconnected dynamics of the fisheries system as a whole. While a full portfolio approach to fisheries management as suggested by Link (2018) is likely years or decades in the future for most U.S. regions, incorporating ecosystem and socioeconomic information into the existing stock assessment process is one step towards more holistic Ecosystem-Based Fisheries Management (EBFM). Efforts to do so are already underway, for example, in the northeast U.S. region, NOAA scientists are evaluating new stock assessment models that include climate information (Saba et al., 2023). Capitalizing on LEK, which has been shown to provide countless benefits to conservation science, can further aid in accomplishing the goals of EBFM and combating many of the challenges currently facing fisheries management, like increasing fishing pressure (Coleman et al., 2004; Felizola Freire et al., 2020) and climate change (Saba et al., 2023; Townhill et al., 2019). In this study, we illustrated how engaging in participatory conceptual modeling with the aid of expert fisheries resource users can increase understanding of the ecosystem and socioeconomic drivers that impact stock dynamics, help better understand sources of uncertainty in stock assessment models, and communicate the linkages and feedback loops between management actions and socio-ecological consequences. We also demonstrated the value of resource user knowledge for informing conceptual models and identifying socio-ecological drivers and linkages that were previously unaccounted for. LEK has been used in various studies to improve fisheries stock assessment (Gervasi et al., 2023b; Mäntyniemi et al., 2013; e.g., Röckmann et al., 2012; Sagarese et al., 2021). Each of these studies used the knowledge of fishermen to inform a part of the stock assessment process. The benefit of participatory conceptual modeling is that it can inform each step of the stock assessment process, thereby incorporating ecosystem and socioeconomic information in a more holistic manner. The specific methodologies we applied to each step are flexible enough to work for any fisheries system.

CRediT authorship contribution statement

Gervasi Carissa: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Matthew McPherson:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Mandy Karnauskas:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fishres.2025.107464.

Data availability

Data will be made available on request.

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