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Are You Thinking What I'm Thinking? A Conceptual Modeling Approach to Understand Stakeholders' Assessments of the Fate of Chesapeake Oysters

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Abstract

The history of oyster management in the Chesapeake Bay is replete with examples of conflict, including an era commonly referred to as the Oyster Wars. Yet, the community of people who work with and depend on oysters has some shared challenges and some stories of success. Using conceptual modeling methods (fuzzy cognitive mapping in particular), we explore whether some stakeholders support and others oppose management proposals because they have fundamentally different predictions for what the outcome of the management actions or other perturbations to the system will be. Stakeholders across the oyster community completed a conceptual mapping exercise as part of the Chesapeake Oyster Summit to describe their perception of how the ecosystem (including humans) functions. This analysis takes those conceptual maps, aggregated by stakeholder group, to model their predictions under currently proposed or frequently discussed management scenarios. Results show more unity than one might expect in how the ecosystem is expected to respond to management initiatives and predicted environmental perturbations. Feedback loops also emerge in some scenarios to either buffer or exacerbate the effects of the management on the ecosystem.

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Introduction

Fisheries management at global, national, and regional scales is increasingly incorporating ecosystem-based approaches in recognition of the need to balance the requirements of multiple sectors and the interactions between a single species with its environment and other species (Christie, et al., 2007; Link, 2010). For oysters, this is especially true, as they serve as a commercial fishery, an important nursery and sheltering habitat, and a cultural touchstone in the communities neighboring reefs (Freitag, et al., 2018). Managing complex systems in the marine realm has proven a challenging goal, and approaches to management have ranged widely over the last few decades as practitioners learn how to implement ecosystem-based management across varied contexts (Tallis, et al., 2010). Each approach relies upon a common understanding of how the ecosystem functions across stakeholder groups. Conceptual modeling can be a powerful tool to not only build that common understanding but highlight areas of the ecosystem with the potential for stakeholder conflict because of conflicting understandings.

Chesapeake Oyster Fishery

The Chesapeake oyster fishery is one of the oldest in the United States, peaking commercially in the early 1900's and subsequently succumbing to overfishing, habitat changes, and disease mortality in the later part of the twentieth century. The political power of the fishery established in its peak remains today, as it structured statewide policy dynamics for the region (Keiner, 2009). The contentiousness of oysters sparked fights between enforcement agencies and watermen in the 1950's that leaves a legacy of divisiveness between many of the oyster stakeholders in the region (Wennersten, 2007), and this tension increases as additional considerations for oyster management are added such as aquaculture, nutrient management, and sanctuary development. That said, recent efforts by the Chesapeake Bay Program, mixed-stakeholder management panels, and interagency workgroups for oyster restoration have managed to bring together politically divided stakeholders towards a common goal of a healthy bay.

Conceptual models

Conceptual model methodology has established itself as useful both for making sense of complex systems and in integrating the social and ecological components of an ecosystem. At the largest scale, they underpin large international agreements as the result of intense negotiation and goal-setting (Diaz, et al., 2015; United Nations Development Programme, 2003). At the smaller scales, they can help identify the root of environmental conflict in a particular community (Delgado, et al., 2009). Conceptual models can help implement and ground theory such as socioecological system management (Ostrom, 2005) or ecosystem service provision (Kelble, et al., 2013) as well as help visualize the differing worldviews and associated cognitive frameworks associated with diverse stakeholder groups (Newell, et al., 2005). This integrative and communicative power of conceptual models are making them popular tools in environmental management scenarios around the world.

One methodology for developing conceptual models is Fuzzy Logic Cognitive Maps (FCMs) (Axelrod, 1976). FCMs are a simplified way of mathematically modeling a complex system (Ozesmi & Ozesmi, 2004), and have been used to represent both individual and group knowledge (Gray, et al., 2012). This approach has been applied to processes and decisions in human social systems, the operation of electronic networks, and in the ecological realm to identify the interactions between social systems, biotic, and abiotic factors in lakes (Ozesmi & Ozesmi, 2003; Hobbs, et al., 2002), nearshore coastal zones (Meliadou, et al., 2012; Kontogianni, et al., 2012), estuaries (Vasslides & Jensen, 2016), and the summer flounder fishery (Gray, et al., 2012).

Given the success and utility of this approach in similar ecosystems and communities elsewhere, the goal of this work is to use FCM to measure how similar the perceptions of ecosystem functioning are across the various stakeholder groups involved in Chesapeake oyster policy and management. The main motive of this exploration is to determine if stakeholders' underlying thought processes about ecological, social, and economic interactions explain the difference in support or opposition for proposed management scenarios. In other words, do some stakeholders support and others oppose management proposals because they have fundamentally different predictions for what the outcome of the management actions or other perturbations to the system will be?

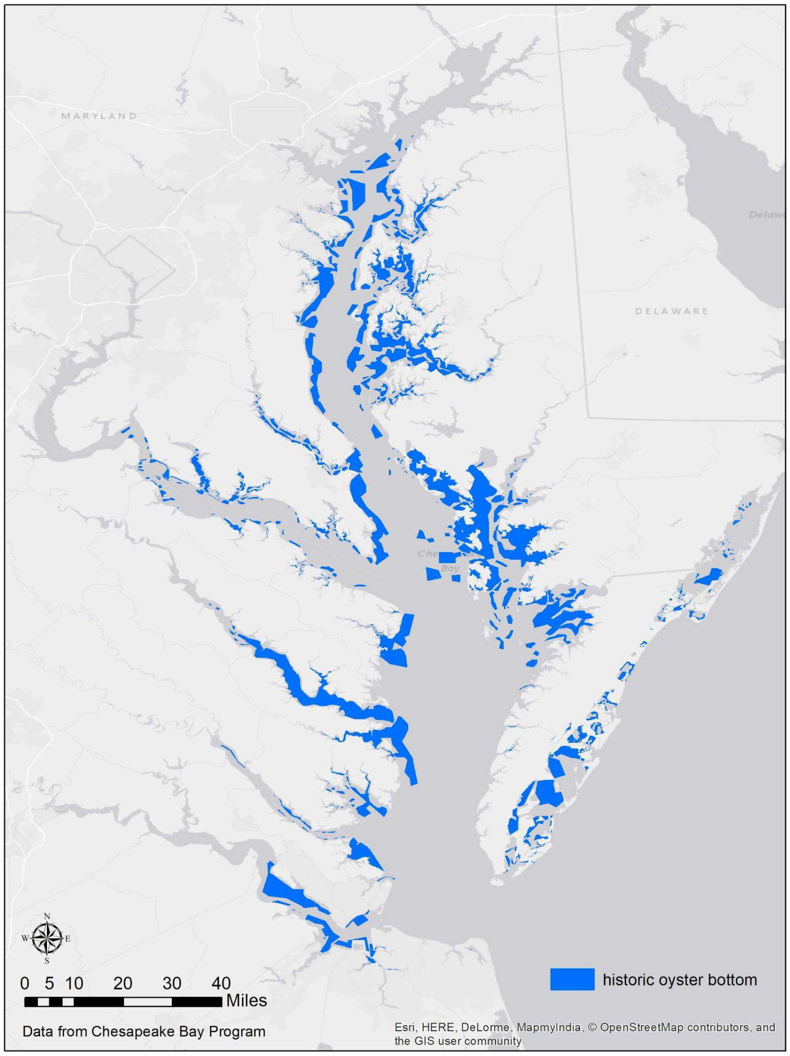
Methods

Study area

The Chesapeake Bay is a flooded river valley formed in the Susquehanna River basin, which drains over 64,000 square miles of land, including the major cities of Washington DC, Baltimore, and Richmond. This is the largest land:water ratio of any watershed worldwide. 18 million people live within this watershed, with an additional 150,000 added each year (Chesapeake Bay Program, 2017). The population pressure and stresses from the land-water relationship create challenges in maintaining water quality, which remains a long-term priority conservation area in the region.

Management of the Chesapeake is notoriously complex, made of many overlapping jurisdictions that require collaboration and coordination. There are also 3,800 species of plants and animals, many of which are under some sort of management mandate at a federal, state, or local level. This is especially true for fish and other aquatic species with developed economic uses, including oysters. The Chesapeake Bay Program coordinates these management efforts and helps identify areas of scientific need for management (Chesapeake Bay Program, 2017).

One of the most defining species of the Chesapeake is the oyster (*Crassostrea virginica*), the shells of which literally paved the roads of many of the region's first towns. Local Algonquian-speaking tribes relied on oysters as an important source of food, especially in the winter. Today, this legacy continues and oysters continue to hold a high degree of cultural importance despite their depleted population (Freitag, et al., 2017). The wild-harvest fishery continues to catch just under 1 million bushels annually, but this is a tiny fraction of historic harvest. Aquaculture oysters are a growing portion of the oyster harvest and surpassed wild harvest in Virginia in 2015 (Hudson & Murray, 2016). In addition, oysters are beginning to be managed as habitat, with a goal of 10 tributaries with restored oyster reefs (Chesapeake Watershed Agreement, 2014) and a network of sanctuaries and designated seed-producing areas in both Maryland and Virginia.



Data from Chesapeake Bay Program

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Figure 1: Map of the Chesapeake Bay indicating the spatial extent of historic oyster bottom, known as Yates Bars in Maryland and Baylor Grounds in Virginia.

The Setting: Chesapeake Oyster Summit

In February 2015, the NOAA Chesapeake Bay Office held an oyster summit in order to bring together the many kinds of oyster stakeholders and help identify ways of working together to meet the commonly held goal of achieving more oysters in the bay. The Oyster Summit was held over two days and was attended by over 100 individuals from across the spectrum of Bay stakeholder groups. The attendees at the Oyster Summit provided the pool of respondents for the Fuzzy Cognitive Mapping (FCM) exercise. The overarching goal of more oysters was served through four main objectives for the summit sessions (NCBO, 2016):

- Share knowledge and identify common objectives for increasing the number of oysters
- Identify needs and opportunities with near-term actions that would benefit Bay oyster populations for all sectors
- Chart a course for sharing needs, opportunities, and suggestions that emerge from the Summit broadly to stakeholders in Maryland and Virginia for input and consensus-building
- Distribute the results of the Summit and next steps to appropriate audiences, tailored for Maryland and Virginia, as appropriate, e.g., scientists, industry, policymakers, and jurisdictional management agencies

These objectives, as well as the topical focus of each of the sessions at the Summit, were negotiated by a Summit Steering Committee consisting of twenty members from across jurisdictions, interests, and sectors of the oyster community who were identified as influential by a network analysis of the oyster community (Freitag, et al., 2018). The steering committee met monthly to plan the summit, and over the course of several of these meetings, participated in a consensus process to determine the priority issues for the oyster community as a whole. The makeup of the steering committee ensured that the diverse interests of the oyster stakeholder community were represented, and members were encouraged and reminded that they should be speaking as a representative for their stakeholder group. These priority issues, which formed the foundations for the FCM exercise, are as follows:

- shell availability and alternative substrates
- larvae availability and resilience
- activity and policy coordination and partnerships
- applying new science and industry developments
- economic and market forces
- water quality (in particular, sediment and nitrogen)
- enforcement and poaching
- new areas that do not currently, but could, have oysters
- community involvement

Fuzzy Cognitive Mapping Model Development

FCMs are conceptual models of a system's operation that are based on key components within the system and their causal relationships to each other. The components can be tangible aspects of the environment (a biotic feature such as an oyster or an abiotic factor such as nitrogen) or an abstract concept such as policy coordination. The important components of the system are linked with weighted, directional arrows. The weighting can range from -1 to +1 (Hobbs, et al., 2002; Ozesmi & Ozesmi, 2004), and represents the amount of influence (positive or negative), that one component has on another.

FCMs can be constructed through an individual interview process (Carley & Palmquist, 1992; Ozesmi & Ozesmi, 2004; Gray, et al., 2012) or in a group setting (Ozesmi & Ozesmi, 2003; Papageorgiou & Kontogianni, 2012). Due to time constraints associated with the summit, the analysis relies on individual contributions from workshop participants created during facilitated activity time. Following the opening plenary remarks, summit participants were given an overview of the project, a promise of anonymity (though they were asked to put a unique identifier on their FCM known only to the authors), and an example of a simple FCM related to an issue outside of the realm of ecology (traffic conditions). Participants were then provided with the list of priority issues created by the summit steering committee (Table 1) to include as components within their conceptual diagrams. As part of a group discussion, participants agreed that "fishing" should also be included in any conceptual model of the system, and that "enforcement" and "poaching" should be separate components.

As part of FCM construction, participants were asked to consider how those components related to one another, using an arrow to indicate direction and to score the strength of the relationship using positive (direct) or negative (inverse) high, medium, or low. Participants were encouraged to begin with the priority issues, but were instructed that they could add or leave out any concepts as needed to fit their description of the system. The session lasted for one hour, during which time facilitators familiar with FCMs were available to answer questions and help guide participants through the process. Most participants completed their FCMs before the end of the session.

Table 1 Key concepts in oyster management used for conceptual modeling activity

Concept Name	**Description**
Oyster	Chesapeake Bay Oyster Population
Shell	Shell availability and alternative substrates
Larvae	Larvae availability and resilience
Policy Coordination	Activity and policy coordination and partnerships
New science and industry	Applying new science and industry developments
Economics	Economic and market forces
Water Quality	Water quality (in particular, sediment and nitrogen)
Enforcement (poaching added)	Enforcement and poaching
New areas	New areas that do not currently, but could, have oysters
Community Involvement	Involvement of community groups

(added) Fishing	Commercial and recreational fishing of oysters and resident fish species

While the map of an individual stakeholder provides information regarding their conception of the important components and linkages within the system, it can be combined with other individuals within a particular stakeholder group to produce a more robust picture of the collective understanding of the system (Gray, et al., 2014). To this end, the individuals were divided into six groups that were determined *a priori* from the Oyster Summit registration and a combined model created for each group: Academia, Aquaculture, environmental non-governmental organizations, Governmental agencies, Hatcheries, and Others (Table 2). In addition, all the individual stakeholder maps were combined into a single map depicting the collective understanding of the system (not presented here).

Table 2 Information on stakeholders who completed fuzzy cognitive maps on the Chesapeake Bay oyster social-ecological system

Stakeholder group	Maps (N)	Occupation/organization/social group
Academia	16	Academic scientists and researchers
Aquaculture	5	Individuals involved in the commercial growing and selling of oysters for consumption
Government	17	Federal, state, county, and local resource managers and scientists
ENGOs	16	Regional, statewide, and local environmental non-profits
Hatcheries	3	Individuals engaged in the spawning and growth of early life history stages of oysters
Others	5	

Data Analysis and Scenario Development

The data contained within an FCM can be analyzed through a variety of methods, many of which are based upon graph theory (Harary, et al., 1965; Kosko, 1991), through the FCMapper package in R (Turney & Bachhofer, 2016). The first step in the analysis process was to translate each individual FCM into a square adjacency matrix, with all of the components on the vertical axis influencing the same set of components on the horizontal axis. The interaction strengths between each of the components were then scored, with high interaction strengths scored as 0.75, medium as 0.5, and low as 0.25 (Harary, et al., 1965).

Individual FCMs were then combined in two ways: by each stakeholder group and across all respondents. To combine maps the connection values between two given components are added, so connections represented in multiple maps are reinforced (provided they have similar signs) while less common connections are not reinforced, but are still included in the map

(Ozesmi & Ozesmi, 2004). To compare connection values across group maps, the summed values are divided by the number of individuals in the group.

By maintaining the initial conditions of the matrix through time, we are able to determine if the model will coalesce around a stable state, go into a limit cycle, or enter into a chaotic pattern (Dickerson & Kosko, 1994). To determine which of these states the conceptual model will reach, the square adjacency matrix of the cognitive map is multiplied by an initial steady state vector (a value of 1 for each element of the vector). The resulting vector is then subject to transformation using a logistic expression ($1/(1 + e^{-1 \times x})$) to bound the results in the interval [0,1] (Kosko, 1987). This new vector is then multiplied by the original adjacency matrix and again subject to the logistic function, repeating these steps until one of the three options is obtained.

If the model reaches a steady state outcome, it is then possible to run hypothetical "what-if" scenarios, where particular components or sets of components are perturbed, to compare the outcomes of the different stakeholder group models. We developed a series of hypothetical scenarios to evaluate based on the main discussion points of the Oyster Summit (Table 3). This included maintaining select components at either high (1) or low (0) values individually, or in combination. This was accomplished by utilizing the same process as described above for determining the stable state, but for each scenario the component(s) of interest in the vector is maintained at either 1 or 0 in each iteration. This process was referred to as "clamping" by Kosko (1986). The difference between the values of the final vector of the clamped procedure compared to the steady state vector describe the relative change within the conceptual model described by each stakeholder group.

Table 3 Hypothetical scenarios evaluated in the stakeholder groups' models.

Scenario name	Component	Clamped Value
Increased Policy Coordination	Policy Coordination	1
Increased Enforcement	Enforcement	1
Increased New Science and Industry	New Science and Industry	1
Improved Shell Availability	Shell Availability	1
Decreased Shell Availability	Shell Availability	0
Increased Larvae Availability	Larvae Availability	1
Decreased Larvae Availability	Larvae Availability	0
"Management Failure"	Policy Coordination Shell Availability Larvae Availability	0 0 1
"Nature Rules"	Policy Coordination Shell Availability Larvae Availability	1 1 0
"Rose-Colored Glasses"	Policy Coordination Shell Availability Larvae Availability	1 1 1

Results

We created fuzzy cognitive maps (FCMs) for 62 individuals that were placed into six stakeholder groupings (Table 2). This represents a 51% response rate overall, with no non-response bias by sector (industry, management, academia, nonprofit). While most individuals included only twelve core components (Table 1), five other components were added by participants (aquaculture, cost, disease, restoration, and seed). The number of components within an individual map ranged from 11-14 (mean = 12), suggesting that the additional components were rarely considered. Furthermore, the average number of components in an individual map was not significantly different between groups (df=5, F=0.561, *p*=0.729; Table 4). There was also no significant difference in the mean complexity (df=5, F=0.871, *p*=0.507) or density (df=5, F=0.457, *p*=0.806) between groups, though Academic, Environmental NGO, and Government participants did tend to have more dense networks. To demonstrate collective perception of the system, the community conceptual model, including all 17 components, is shown in Figure 1.

Table 4 Graph indices by stakeholder group. All values are means with standard deviation shown in parentheses.

	Academic	Aquaculture	ENGOs	Government	Hatchery	Others
Number of components	12.125 (1.088)	11.6 (0.548)	11.875 (1.015)	11.823 (1.015)	11.667 (0.577)	11.4 (0.548)
Number of connections	20.75 (8.412)	14.2 (4.604)	20.125 (8.891)	20.176 (7.854)	15.667 (2.517)	17.6 (4.336)
Number of transmitter components	2.438 (1.861)	3.0 (1.732)	3.125 (2.680)	3.176 (2.038)	5.667 (1.155)	2.6 (1.949)
Number of receiver components	0.875 (0.885)	1.4 (1.517)	1.125 (1.310)	0.588 (0.795)	0.333 (0.577)	0.8 (0.837)
Number of ordinary components	6.625 (2.604)	4.8 (1.48)	6.25 (3.172)	6.47 (2.154)	4.333 (1.154)	6.6 (2.966)
Complexity	0.298 (0.341)	0.313 (0.473)	0.487 (0.664)	0.210 (0.313)	0.048 (0.082)	0.438 (0.427)
Density	0.142 (0.056)	0.107 (0.039)	0.146 (0.067)	0.147 (0.075)	0.117 (0.029)	0.151 (0.056)

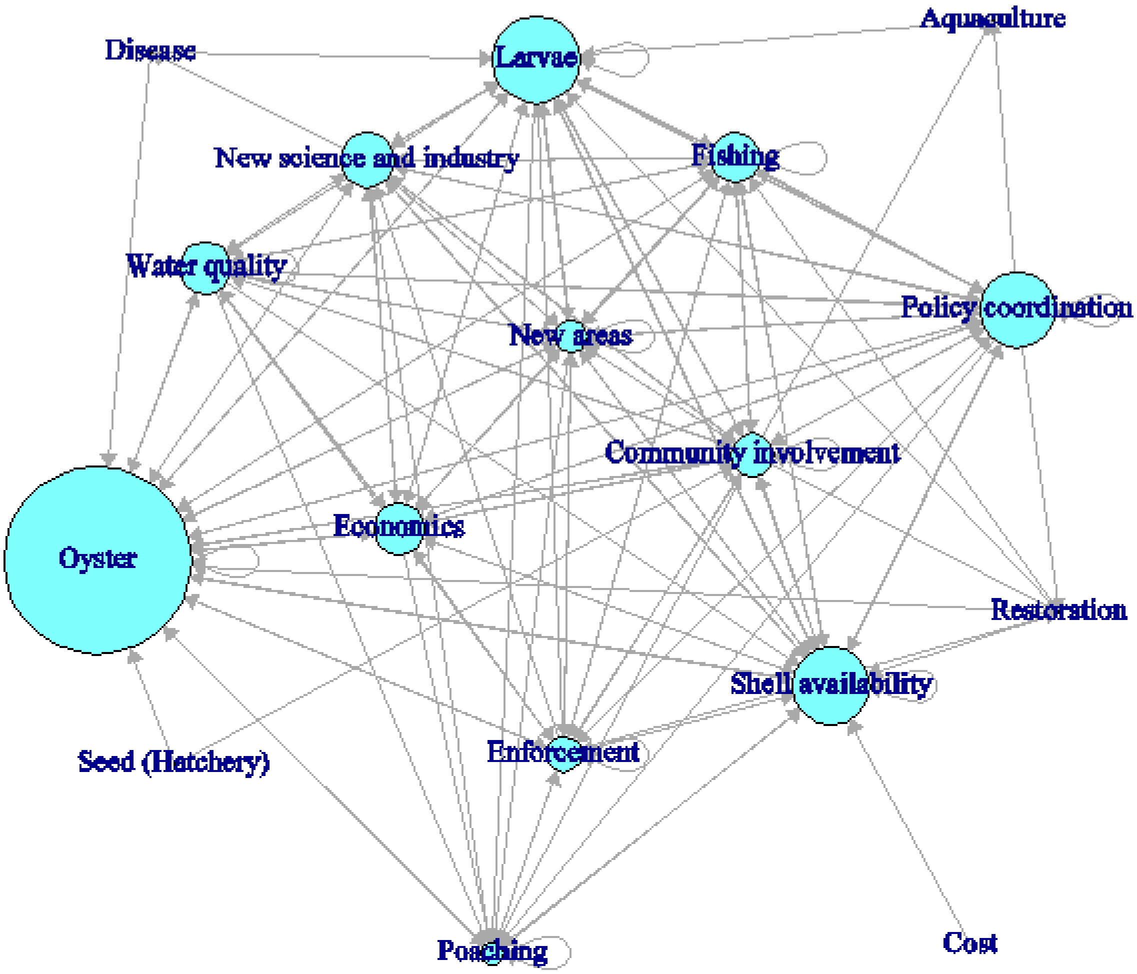

Figure 1 The community conceptual model. Node size is related to the sum of the strength of the interactions associated with each node.

Scenario results

Through each of the stakeholder group's collective fuzzy cognitive models (FCMs), the outcome of future scenarios can be predicted. The scenarios depicted here are either existing proposals for the Chesapeake region or scenarios that are frequently discussed in management forums (including the Oyster Summit) (summarized in Table 3). As a reminder, these FCMs underpinning the modelled scenarios are not depictions of how the system behaves for certain (i.e. no FCM describes absolute truth), but instead, they are models of how different stakeholder groups understand system function. The value in these models, and the scenarios described here, is in thinking how the different stakeholder groups' models align or do not align and in highlighting how the complexity of the system may lead to some unanticipated results.

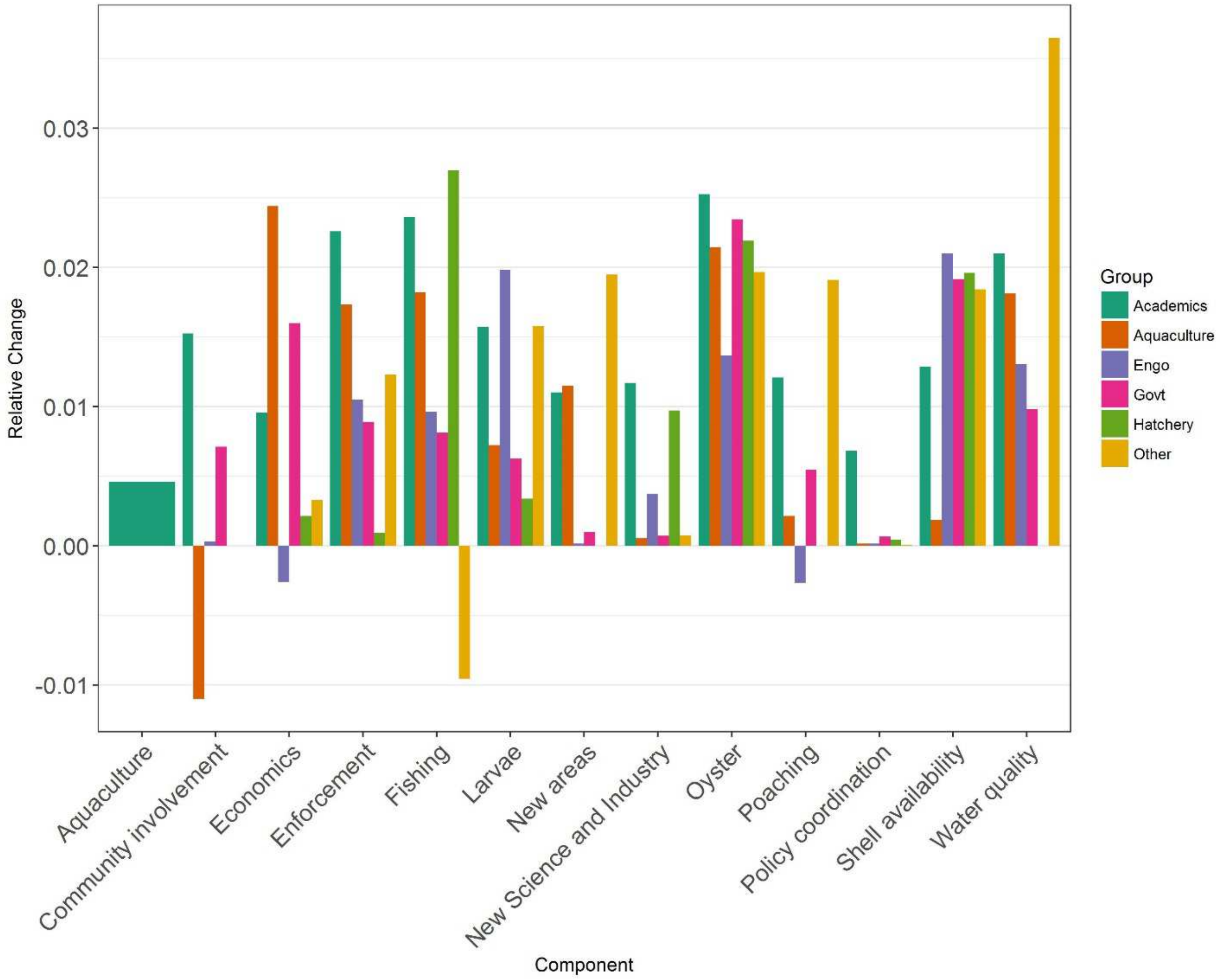

Figure 2 The Increased Policy Coordination scenario.

The driving purpose behind events that bring together multiple sectors across the region, like the Oyster Summit, is to increase policy coordination (Fig 2), with an aim that the consistent application of best practices will benefit oysters. Thus, it is not surprising that the models predict a positive response in most components to improved policy coordination. There are a couple of counter-intuitive responses contained within the models, however. It appears that the models for many participants suggest a positive relationship between policy coordination and poaching.

While some of the individual models contained a positive direct linkage between the two components, it is more likely that the positive response in poaching is mediated through the predicted increase in oyster biomass (which encourages more poaching). The other negative responses to increased policy coordination are through direct linkages in the respective models, and likely reflect that group's perspective on the issue.

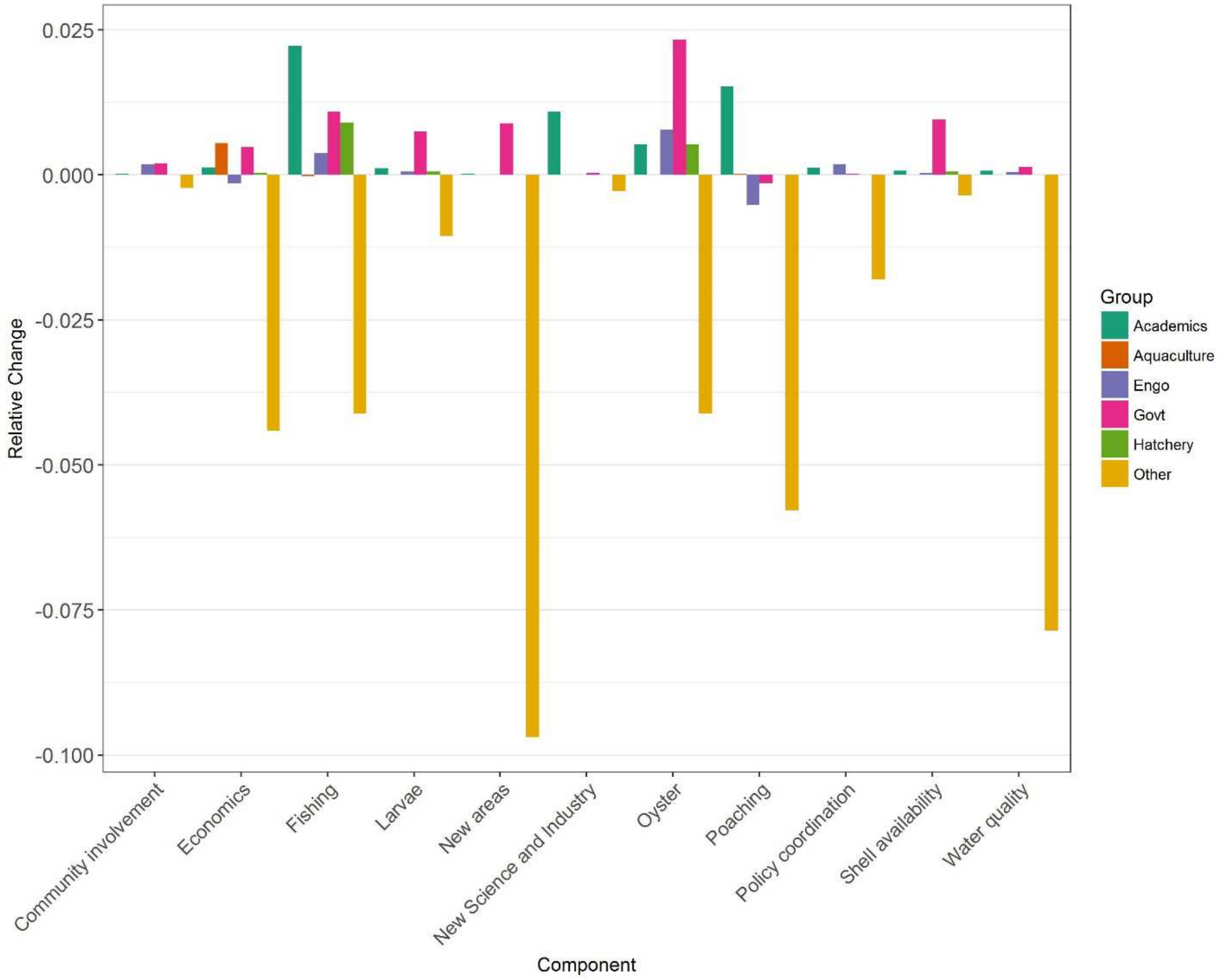

Figure 3 The increased enforcement scenario.

Increased enforcement capacity is a near-constant request from natural resource law enforcement agencies who are charged with implementing oyster regulations, especially as they must cover vast geographies with some of the highest waterfront access in the country. However, as indicated by their conceptual models (Fig 3), the oyster community as a whole sees increased enforcement as a bit of a mixed blessing with only small increases in oyster population overall. The strongest believers in negative outcomes were those in the "other" category, which included people with mixed backgrounds: the commercial wild-harvest watermen, and other oyster-related businesses. These stakeholders tended to be more negative than the others in many of the scenarios. Enforcement, to most people, would encompass the enforcement of poaching rules, so it is interesting to see from this model that stakeholder models are mixed as to whether enforcement would lead to a decrease in poaching. This may be due to the feedback loop between more oysters leading to more poaching, which increased enforcement may not have the capacity to cover. Overall, enforcement turns out to be a more complex issue than expected and is predicted by the oyster community to only yield small changes either way, so may not be the panacea presented in the common requests for more enforcement.

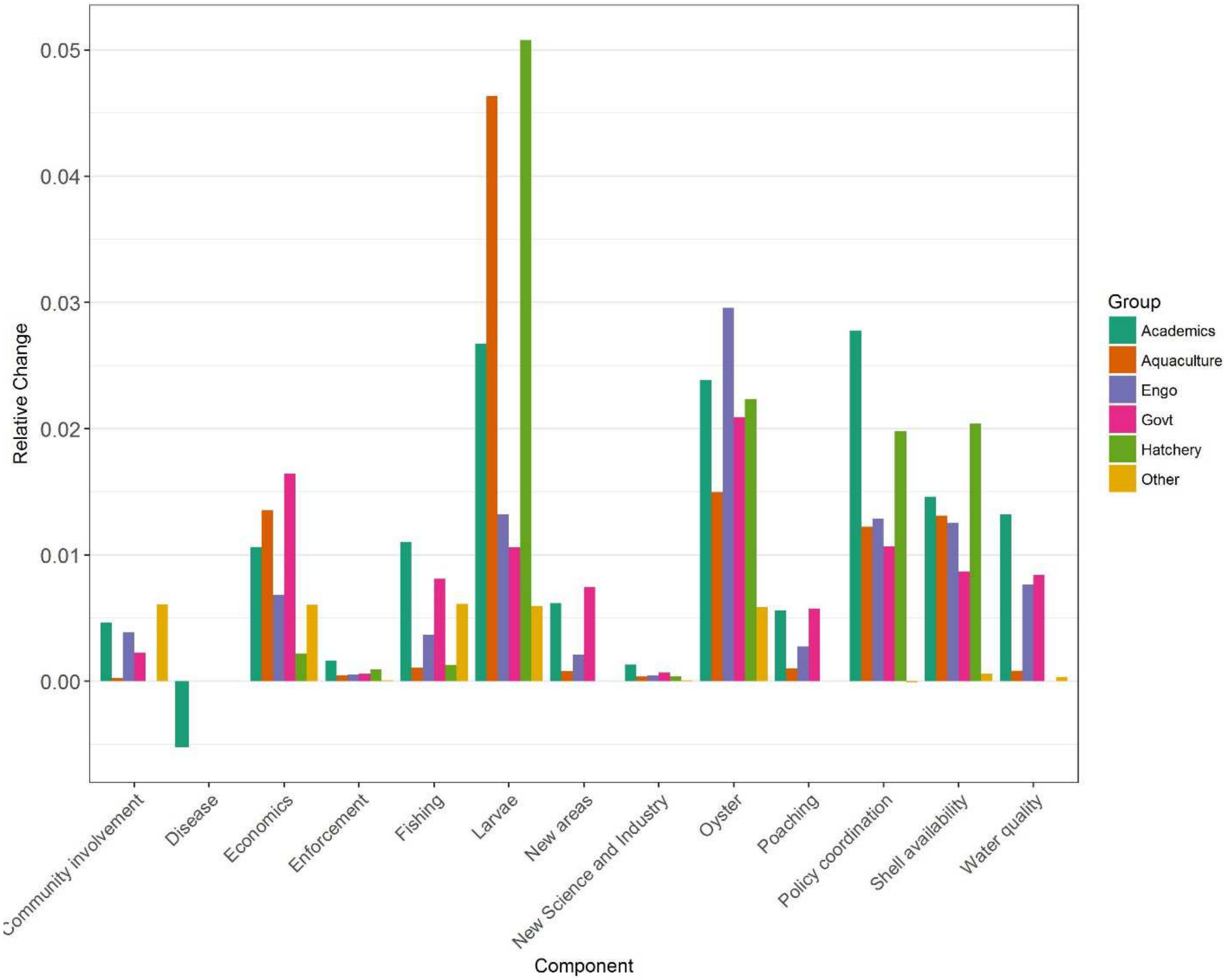

Figure 4 The new science and industry scenario.

New science and industry also represents a common policy and funding request, encompassing a wide range of research and development activities from basic oyster biology to directly applied industrial research. All of the models lead to positive outcomes for all components, except for disease, under an increase in new science and industry (Fig 4). Notably, the four areas of major interest to the Summit Steering Committee (larval availability, oyster production, policy coordination, and shell availability) all see robust increases. Academics and hatchery industry participants tended to be most optimistic about the potential outcomes of increasing science and industry, though aquaculture and government participant models reflect the largest increase in economics. Perhaps most interestingly, despite the current climate of scientific mistrust seen in many aspects of natural resource management (Oreskes & Conway, 2011), all of the participants in this exercise agree about positive (albeit slight) benefits of increasing science activity.

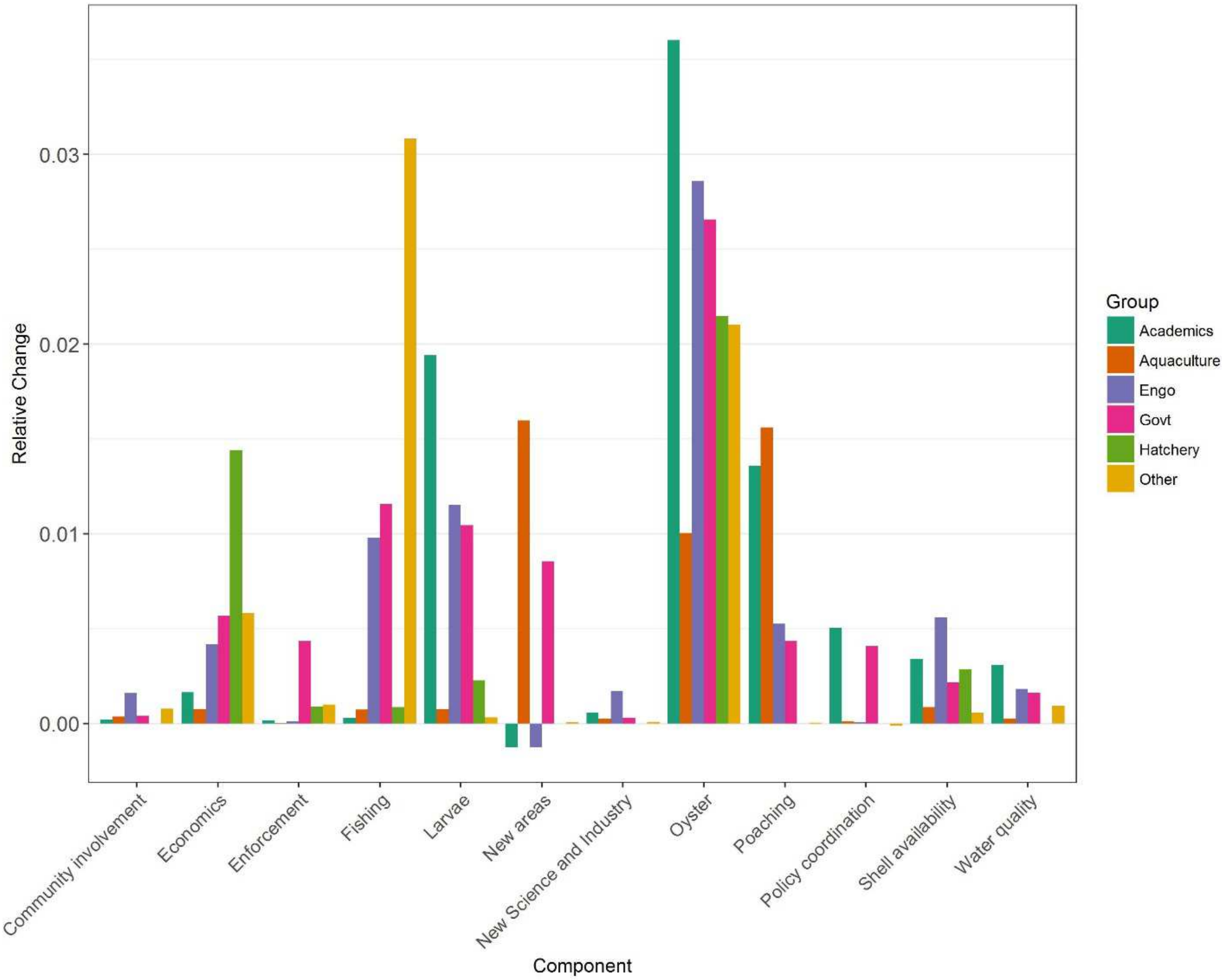

Figure 5 Increased shell availability scenario

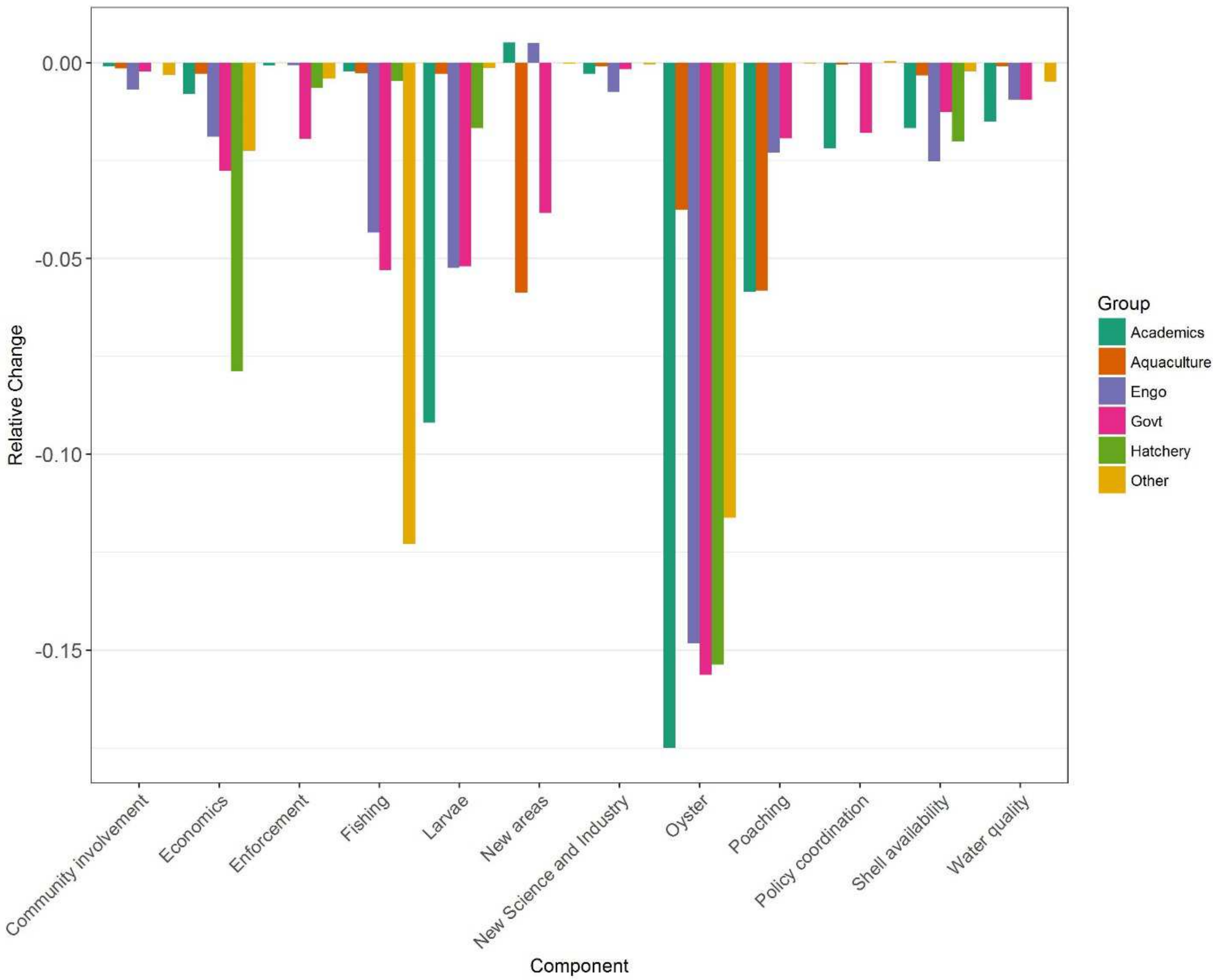

Figure 6 Reduced shell availability scenario

Shell (and other hard substrate) is necessary for oyster spat settlement and the lack of hard substrate is widely considered a limiting factor for increasing the populations. Shell availability is decreasing in the Chesapeake, reflected in rapidly rising shell prices and increased efforts by industry to retain shell for production. Given this limitation, it is unsurprising that increased shell availability had positive outcomes for all model components (Fig 5). This result was virtually unanimous across stakeholders. Academics and ENGOs models showed that increased shell would have a slight negative effect on opening new areas for production. Their conceptual models showed a slight direct negative connection here, perhaps because new areas would limit dredging activity currently used to collect fossil shell.

Conversely (in what could be considered a business-as-usual scenario), decreased shell availability had negative outcomes for all model components (Fig 6), though at a higher magnitude than predicted for the increased shell scenario. This would be expected given the understanding of shell as a limiting factor (NCBO 2016), which below a certain quantity would lead to a tipping point beyond which larval mortality increases from inability to find substrate – in the absence of substrate oyster spat can suffer almost total mortality from blue crab predation (Krantz & Chamberlain, 1978).

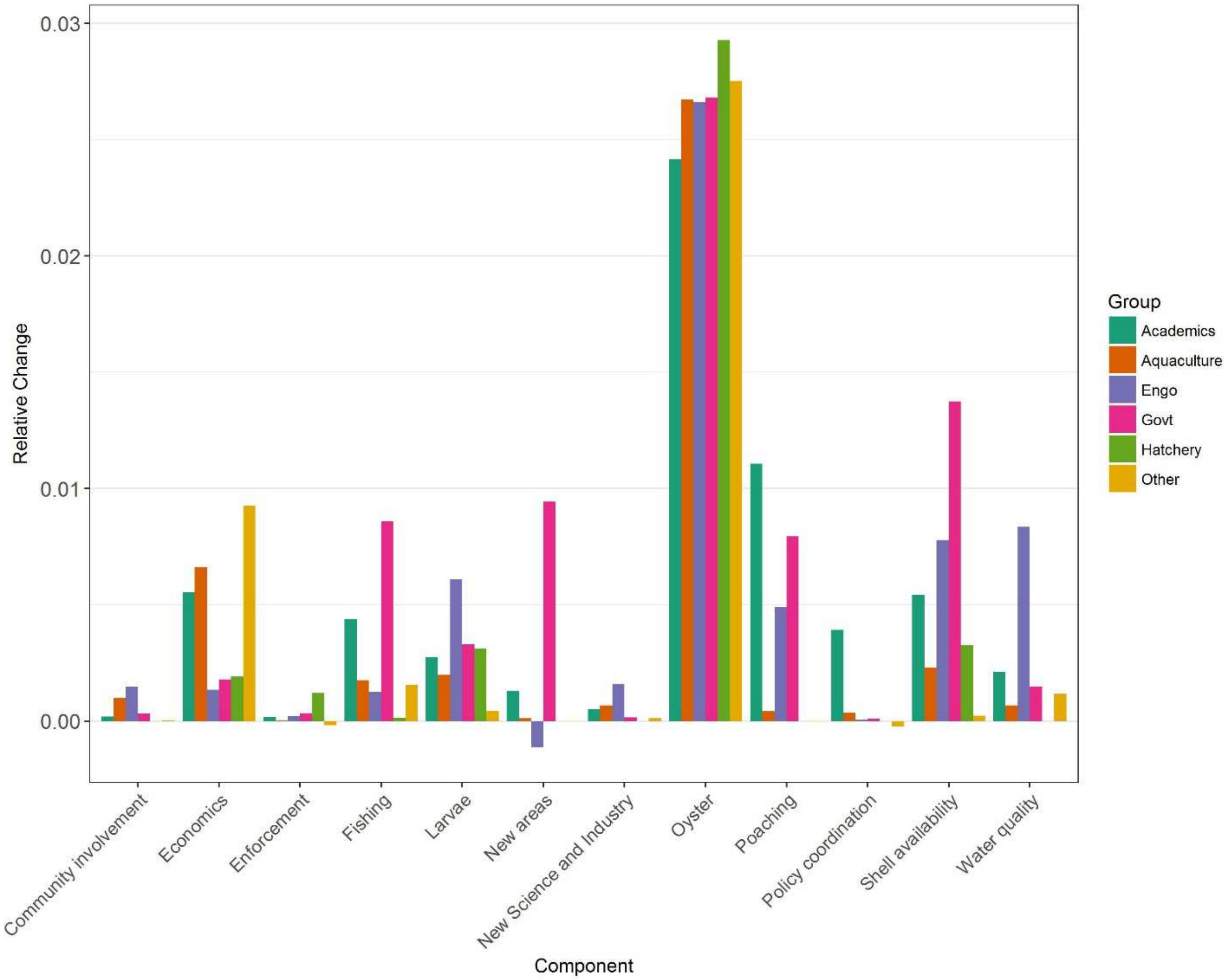

Figure 7 Increased larval availability scenario

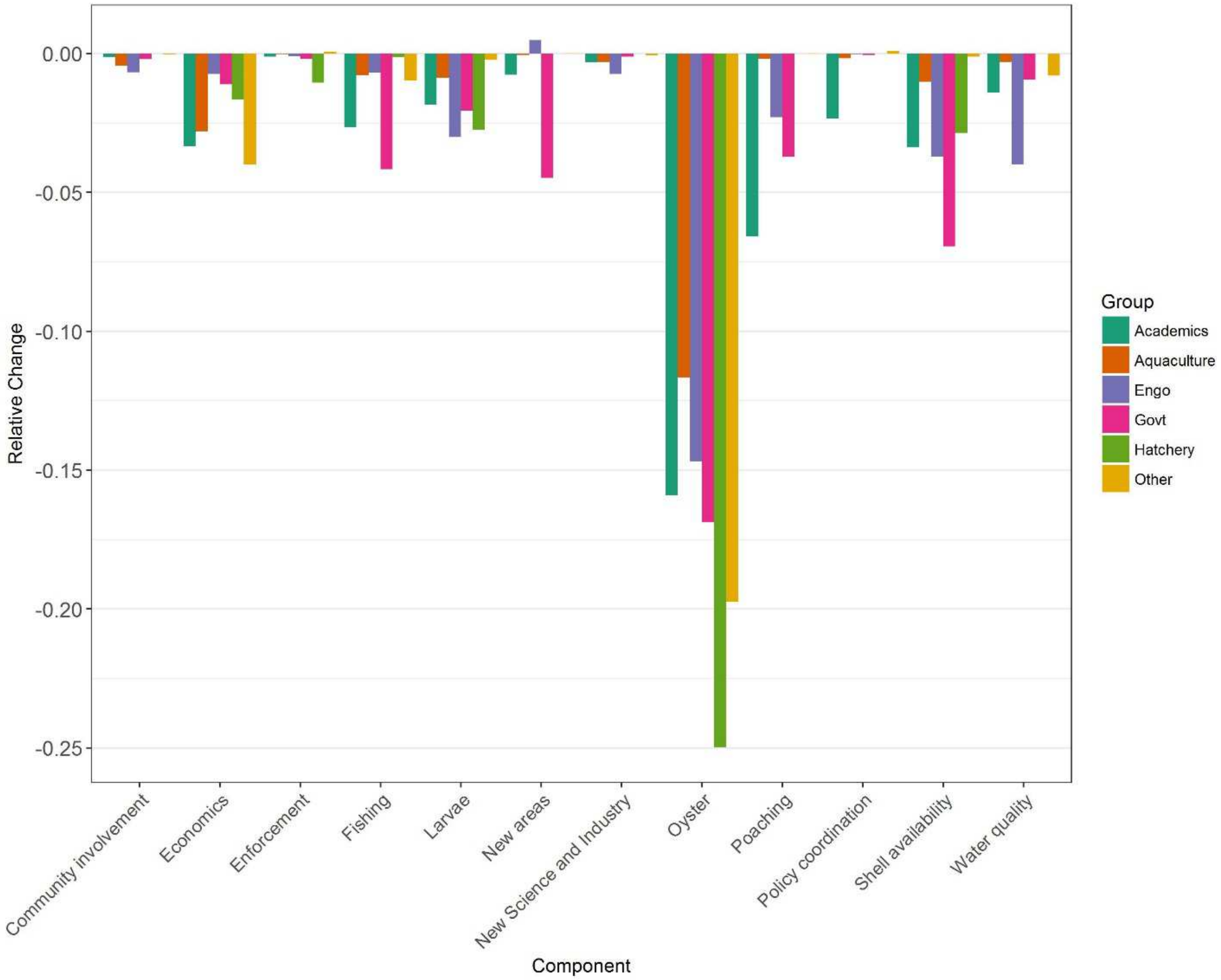

Figure 8 Reduced larval availability scenario

Larval availability is a high-priority policy issue, motivating the creation of larvae-producing sanctuaries in upstream locations and public funding for hatcheries to subsidize natural supply. According to stakeholder models, more larvae primarily leads to an increase in oyster population, with much smaller increases in other parts of the system (Fig 7). This is expected, as additional larvae that survive will grow into adult oysters given time, and the stock will reproduce and the cycle will continue. Note that government stakeholders show bigger increases in multiple system factors, potentially because government stakeholders view larvae as more of a limiting factor to the system than other resources and concepts within our conceptual model.

Reduced larval availability mirrors the predictions of increased larval availability, but in higher magnitude (Fig 8). Like the shell availability scenarios, there may be a threshold effect occurring here: if larval availability decreases further, it is more likely to become a limiting resource to the system. While there may be sufficient larvae now such than an increase only yields marginal results, a decrease might push the system below a minimum number of larvae needed to produce the next generation of healthy oysters. Since there are already programs in place to increase larval availability, maintaining the status quo requires maintenance of these programs.

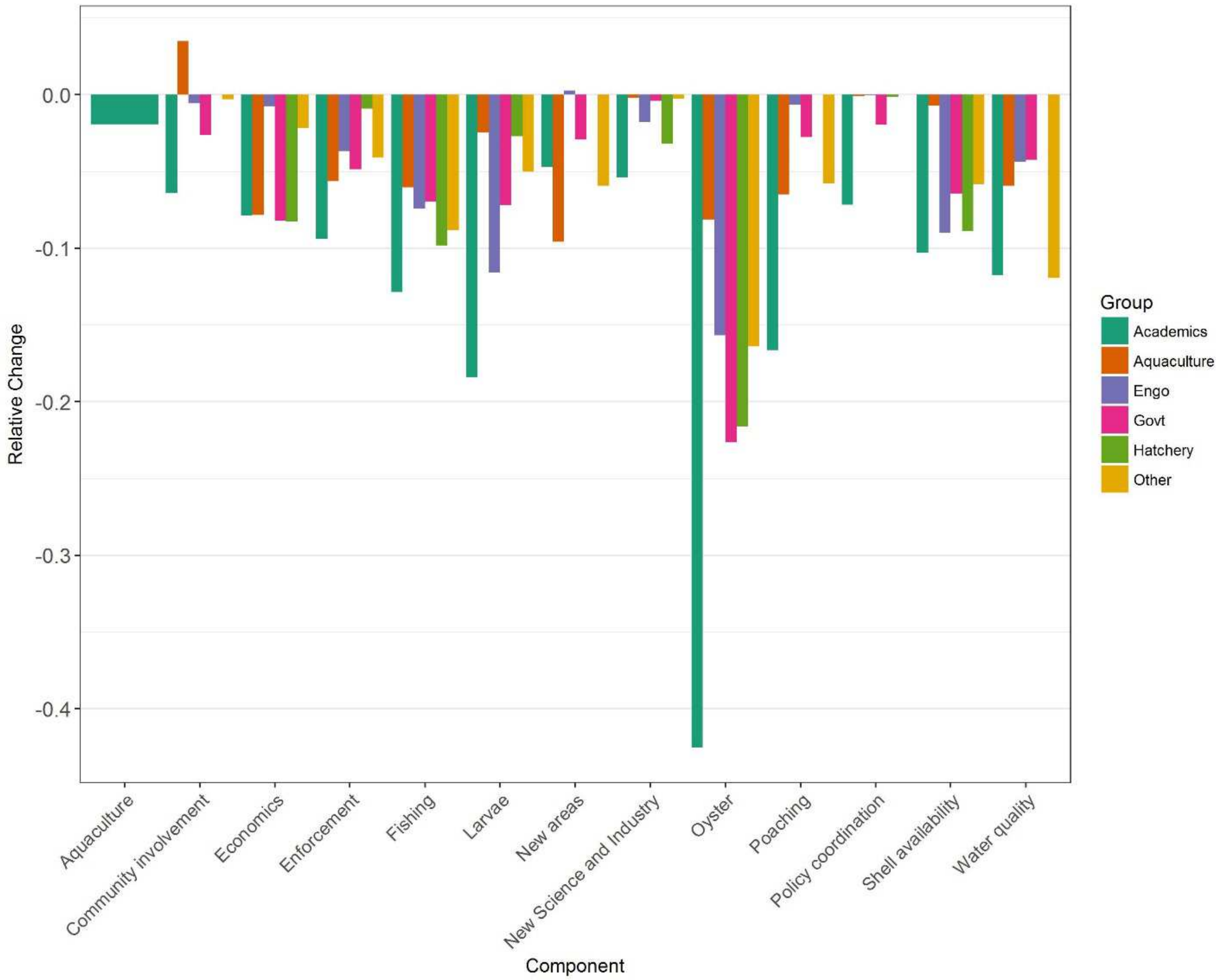

Figure 9 The "Management Failure" scenario

In this “Management Failure” scenario, a clear consensus across all stakeholder models and virtually all concepts is evident (Fig 9). This scenario models what would happen when natural forces promote larval availability but management cannot coordinate or provide shell subsidies common in Bay jurisdictions. This scenario had the highest magnitude change on the oyster population of all the tested scenarios. This suggests that stakeholders consider management efforts to support policy coordination and prevent loss of shell are necessary to prevent drastic declines in the oyster population.

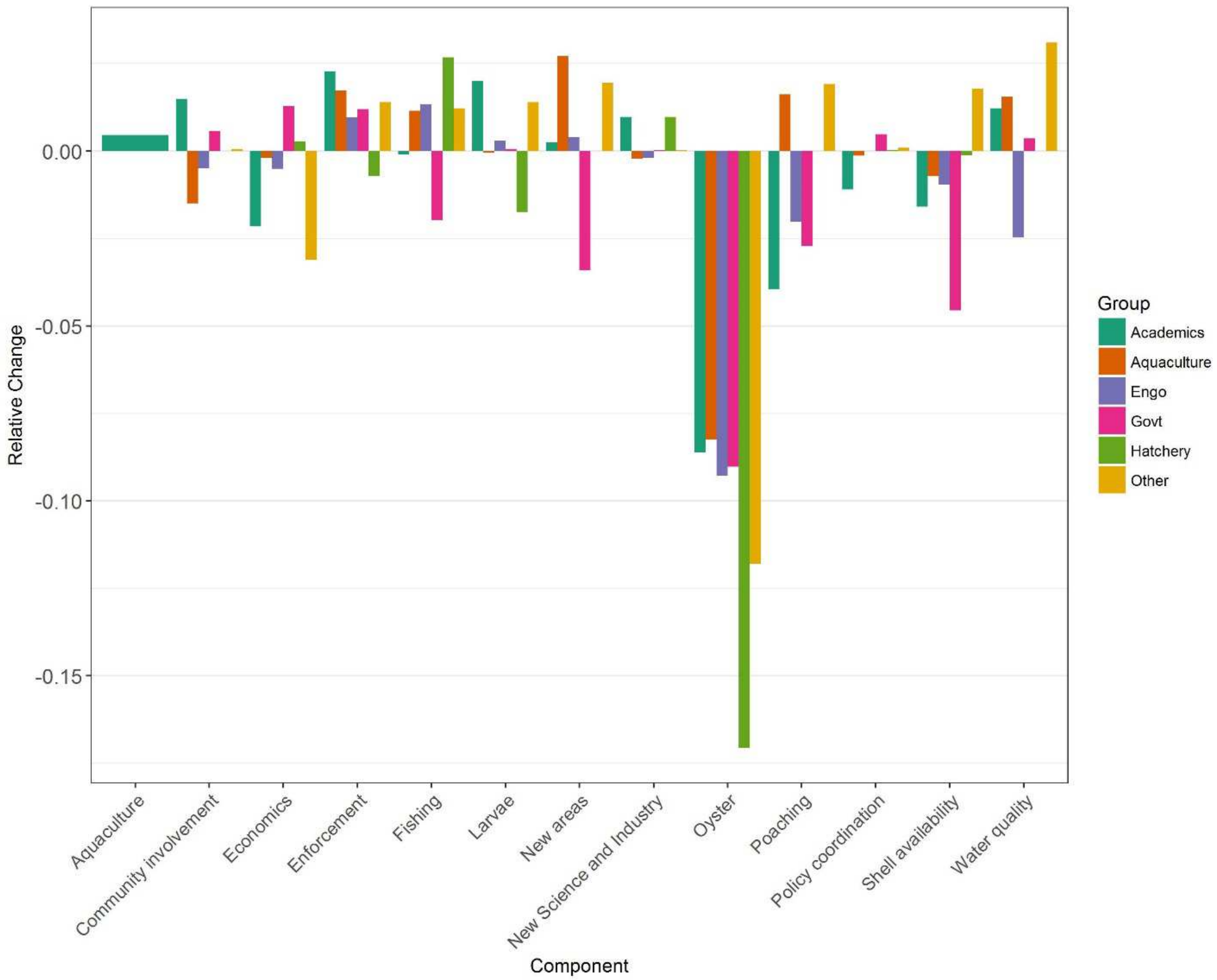

Figure 10 The "Nature Rules" scenario

When a scenario where management is optimal and shell availability programs are well-stocked but nature does not provide larvae, the stakeholder's models produce mixed results (Fig 10) in everything but oyster population. The predicted oyster population drop aligns with the models only looking at reduced larval availability and suggests that the participants feel that larval availability is a critical component controlling the oyster resource. Even with improvements in components that are within resource managers' control, the biology of the resource exerts a deterministic influence. The lack of agreement among models for other factors reflects uncertainty among participants or differing perspectives between groups on how the other components of the system would respond to this condition. The mixed results also reflect the unanticipated responses that can occur when well-connected models are perturbed in multiple ways. Oyster population loss would have been predicted at an even higher magnitude had the effects of the scenario not been buffered by other concepts in the model, as depicted by feedback loops in several stakeholder group models. While small in magnitude, this may suggest a resiliency within the system that may otherwise go unnoticed.

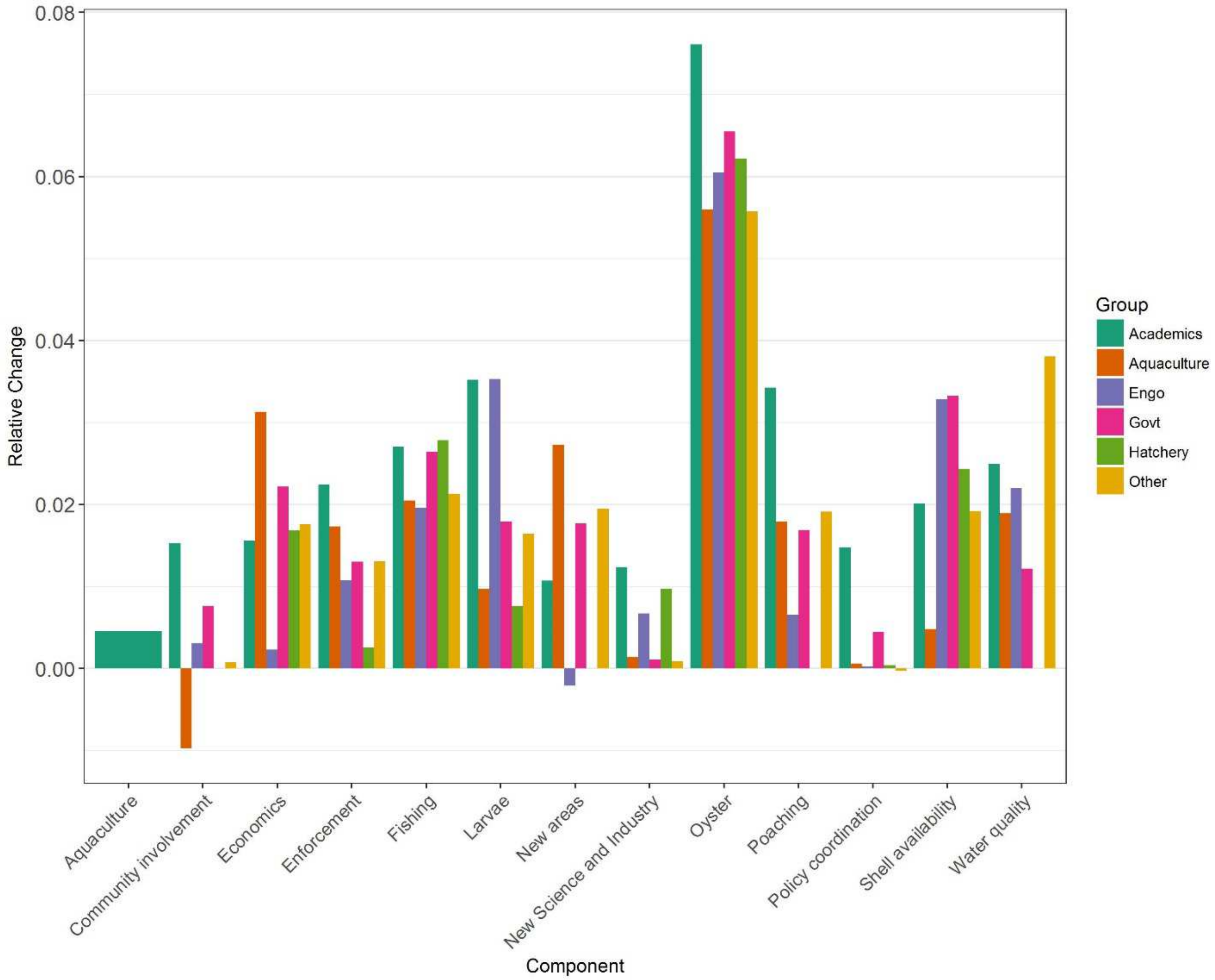

Figure 11 The "Rose-Colored Glasses" scenario

Looking at the oyster world with optimism yields a scenario where the largest issues identified by participants are resolved: policy coordination improves, shell availability rises, and larval availability rises. In this optimistic scenario, one can draw some conclusions about the magnitude of changes likely to occur even when everything is running smoothly, and this can be helpful to scale expectations. Note that this magnitude is higher than any of the individual scenarios, indicating that there are positive feedbacks creating synergies in the system. This makes sense given the structure of the conceptual models, since many of the concepts are densely connected. This synergy also tempers the negative community involvement expected from aquaculturists, but is a reminder that even with all positive changes, there are still tradeoffs to consider in the system. The synergy also supports pursuing multiple policy changes simultaneously in order to achieve the positive feedbacks between them.

While the perturbations in the “Management Failure” scenario are the opposite of the “Nature Rules” scenario, the effects are not mirror images of one another. Unlike the distinct negatives observed across all factors in the “Management Failure” scenario, the “Nature Rules” scenario offers some mixed results that emphasize the feedbacks present in the system. However, the across-the-board positive impacts for the “Rose-colored Glasses” scenario add evidence that

Chesapeake oyster ecosystems require good management (e.g., policy coordination and obtaining new shell/substrate) to prevent a precipitous decline. In addition, strong recruitment is necessary to achieve an increase/recovery of the population.

Discussion

A stakeholder-based fuzzy cognitive mapping (FCM) modeling approach can be used to understand the patterns and relative magnitude of changes that can be expected given proposed management actions in systems where research-derived data is not available for all of the components (Vasslides & Jensen, 2017). By asking stakeholders to form their conceptual model of the oyster resource in Chesapeake Bay - whether developed through formal science, experiential knowledge, or a combination of both – the methods place different ways of knowing on equal standing, while at the same time capturing the broadest possible perspective. This is particularly useful in ecosystems with a large body of local ecological knowledge, where considering many ways of knowing are critical to fully understanding and managing the resource.

When the model perturbation scenarios are considered together a pattern emerges. Individual positive management and policy changes (i.e., increased policy coordination, increased enforcement) resulted in slight increases for oysters and other nodes across virtually all stakeholders. Individual positive biological changes (i.e., increased larval and shell availability) similarly resulted in overall slight, positive changes for oysters. Conversely, negative perturbations to these biological nodes, resulted in overall larger, negative increases. For individual perturbations scenarios, positive perturbations primarily produced positive population changes in oysters.

Combined perturbation scenarios show similar trends and illustrate the need for positive changes in both policy/management and biology. The Management Failure scenario shows that without policy coordination and adequate shell, recruitment increases alone will not result in oyster population increases. The Nature Rules scenario supports this conclusion, though with mixed results in other model concepts. However, combined positive changes in policy coordination, shell/substrate availability and larval availability showed strong positive increases for oysters.

This modeling exercise targeted collective understanding of the ecosystem, specifically comparing stakeholders’ perceptions about factors influencing the Chesapeake Bay oyster population. To facilitate comparison, we seeded the modeling exercise with guidance from the steering committee (scaled to level of specificity, using shared terminology). Limiting the concepts may have artificially enforced similarity in models, and as a result similarity in conclusions about system perturbations. However, other concepts were added by the participants as they needed. For example, restoration was added as a concept by one stakeholder group. Initially, the Steering Committee specifically left restoration off the list because of overlap with other concepts and confusion over restoration *to what*. Overall, so few concepts were added that concerns about similarity in model perturbation results are limited. In other words, similarities in stakeholder models is more likely attributable to actual similarities in their views and not an artifact of our methodology.

These conceptual models are based on the perceptions of stakeholders, so they are not necessarily reflective of actual socioecological interactions; however the wisdom of the crowd phenomenon (Galton, 1907) suggests that collectively, they will be close even for complex, managed ecosystems (Brown, 2015). While the collective model therefore is more likely to reflect reality, where certain stakeholder groups diverge may reflect something about their social interactions as well. For example, those in the “other” category of stakeholders fall on the outer edges of the social network of the Chesapeake oyster community, at least as far as advice sharing is concerned (Freitag, et al., 2018). Similarly, the general level of agreement reflects the well-connected advice network as opposed to the perceptions of conflict and disconnection between stakeholder groups (Freitag, et al., 2018).

Though comparing these conceptual model scenarios to established ecosystem descriptions is difficult, the fact that the dynamics in the FCMs are supported by scientific literature, picked up across all the groups - not just those expected to be familiar with the science- is reassuring. For example, the strong negative response to decreased shell substrate and larva, compare to the slight, positive increases to increases in these components is consistent with population dynamics principles (Wilberg, et al., 2011) and the science of tipping points (Berrouet, et al., 2018). Similarly, the dynamic between enforcement and poaching is supported by the common pool resources literature that describes the relationship between enforcement and poaching in terms of incentives, with poachers balancing potential financial gains with social norms, regardless of enforcement capacity (Ostrom, 2005).

This conceptual modeling exercise emphasizes optimism that is often lost in long-term environmental challenges, including efforts around oyster reefs: that there is consensus among stakeholders that with a little luck from nature in providing larvae, good management and policy can create more oysters and related positive outcomes. Of course, there are differences in the details of that overall conclusion, but encouraging stakeholders to take a system view enables that optimism and bigger picture to emerge and could be a way for managers to set a tone of collaboration toward shared goals in the often-fraught management arena.

The similarity between models also shows that in addition to consensus on creating more oysters, there is also strong agreement if not consensus in which major issues need to be addressed to meet that ultimate goal. For example, all the policy coordination and shell budget increases in the world cannot make up for a situation where nature leads to bad larval production. In a way, then, the consensus is that there is still a big question mark over the future of oysters in the Bay depending upon how the pieces come together. Opportunities where these conceptual models show agreement offer opportunity to move forward on aspects under human control (i.e. policy coordination, and to a degree, shell budget).

While the high degree of similarities in the model outcomes suggest there are a number of avenues for the various sectors to work together to advance oyster restoration in the bay, the areas of disagreement also present opportunities, though of a different type. When the models, or model outcomes, diverge across multiple groups, it may represent a component or relationship that is not well understood, and is thus an avenue ripe for further scientific exploration. If the degree of divergence is limited to one, or a minority of groups, the underlying difference(s) may be due to a knowledge imbalance, where recently identified facts have not been adequately disseminated to all of the stakeholders. This can be remedied through appropriate knowledge sharing efforts, which can lead to greater engagement across the community.

The relatively high degree of agreement between the stakeholder groups in their responses to potential management actions suggests that there is a high degree of consensus between them regarding the operation of the system. This is also reflected in the structural similarities of their FCMs (density and complexity, Table 4). This consensus should be stressed in future management considerations; in effect, there is far more that the various stakeholder groups agree on than disagree on, though they may not realize it. This consensus can set a collaborative tone in future management negotiations while focusing conflict on specific areas of disagreement where solutions such as additional research may prove conciliatory.

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