ENVIRONMENTAL SCIENCE & POLICY 45 (2015) 109–122

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/envsci

The use of participatory modeling to promote social learning and facilitate community disaster planning

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ARTICLE INFO

Keywords:
Adaptive capacity
Climate change
Disaster
Mental models
Resilience
Social learning

ABSTRACT

Coastal island communities face significant risks associated with increased natural hazards and other impacts associated with climate change. Further, deeply rooted social issues, lack of awareness or information, and inadequate infrastructure and planning may exacerbate risks to island socio-ecological systems. Understanding these relationships is often difficult, given the lack of methods available for communities to explicitly explore anticipated risks and potential adaptation strategies, in relation to the characteristics of their community socio-ecological system. Social learning has also been shown to foster adaptation to environmental changes, build social trust and empower diverse stakeholders, by offering opportunities for groups of individuals to challenge, negotiate and propose new norms, policies or programs. We present a three-phase social learning framework to facilitate stakeholder-driven scenario-based modeling, in order to inform community disaster planning in relation to the potential impacts of a tsunami. The participatory research was conducted in conjunction with a community disaster committee, representing the communities of the North Shore of O'ahu, Hawai'i. Through a series of iterative participatory modeling workshops using fuzzy-logic cognitive mapping, the community committee represented, explored and actively questioned their beliefs about the natural hazards that their community faces. Further, the modeling process allowed the committee to represent the communities' dynamic nature, run tsunami hazard scenarios to quantify potential direct and indirect effects, and explicitly compare trade-offs of competing adaptation strategies. Changes in the committee's model representations that took place over time demonstrate a progression through single-, double- and triple-loop learning, indicating that social learning occurred across individual to institutional levels, and over short- to long-term time scales.

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http://dx.doi.org/10.1016/j.envsci.2014.10.004
1462-9011/

1. Introduction

The Hawaiian Islands are vulnerable to natural hazards and the impacts of climate change, due to their geographic remoteness and large dependency upon imported food and energy (Kaly et al., 2002). Historically, communities comprised of native Hawaiians and long-term residents have utilized place-based strategies to maintain their resilience, however community members now report that fragmentation, tourism and globalization have weakened the collective social memory and legacy effects of past disasters (Vaughan and Ardoin, 2013). As a result, these communities are more prone to rely on aid after a disaster occurs, which does not improve long-term adaptive capacity (Birkmann, 2006). A comprehensive multi-sector approach is needed to improve disaster planning and build more resilient communities (Folke et al., 2002; Walker et al., 2002). Analysis of key physical, social, economic and environmental system factors is critical in order to reduce vulnerability and enhance coastal resilience to long and short term ''shocks'' to these communities (Birkmann, 2006). This includes developing methods for communities to collaboratively articulate the potential impacts of hazards and climate change, in order to define the anticipated outcomes of various adaptation strategies.

Community-based resilience planning will have a higher probability of success if stakeholder-driven community descriptions, community resources and the issues of concern (Abarquez and Murshed, 2004; Adger, 2003; TRIAMS, 2006; USAID, 2007) can be formalized into a set of scenarios that capture the major uncertainties in the system's future dynamics (Walker et al., 2002). This paper outlines a methodology that standardizes diverse stakeholder knowledge and management strategies in a form that maintains the integrity of complex human understanding and is useful for analyzing a community's dynamics in relation to natural hazards. Additionally, we present data that measure changes in the community's model over time as evidence of conceptual change among community members. This research draws from several distinct yet related bodies of literature on: (1) representing individually held beliefs (e.g. mental models) in the planning process; (2) allowing agreement or inconsistencies in beliefs to be discussed as a way to facilitate structured social learning; and (3) understanding how learning occurs as a result of engaging in scenario analysis to improve the adaptive capacity of communities in relation to environmental change.

To adapt to change, communities must be able to anticipate a problem, collect and share knowledge about it, reflect, and together develop a shared vision for action (Tschakert and Dietrich, 2010). However, tools and processes that promote such interaction in an organized and participatory manner in real time are somewhat limited (Walker et al., 2002; Gray et al., 2013) although significant advances have occurred in recent years (Voinov and Bosquet, 2010). Here, we suggest that actively representing individual and group beliefs through a mental modeling exercise, facilitated by the development of fuzzy-logic cognitive mapping (FCM) supports structured deliberation around coastal hazards and provide a way for diverse community members to construct and revise their knowledge over time.

Mental models are individually and internally held cognitions of external reality that are used to code, filter, and interpret the external world, allowing individuals to reason, explain and interact with their surroundings (Jones et al., 2011). Mental model representations enable individuals to reason and make decisions, similar to a computer simulation, allowing different scenarios to be examined (Johnson-Laird, 1983). Sharing mental models is a conduit to improve stakeholder communication and reduce collaboration barriers, by (1) utilizing visual participatory processes contributing to clear and open communication; (2) overcoming obstacles to incorporating multiple sources of knowledge (Rodela, 2011; Reed et al., 2010); (3) enabling shared ownership of a conservation plan (van der Wal et al., 2014); and (4) improving social assessments (Biggs et al., 2011).

Change in mental models is considered to be a type of learning (Chi, 2008). Mental models can be changed through interactions between stakeholders of a given social network (Reed et al., 2010) by sharing ideas through a deliberative process that facilitates social learning. Promoting learning through guided interaction has been found to foster understanding of socio-ecological systems (Walters and Holling, 1990; Walters, 1986; Reed et al., 2010; Holling, 1978). Social learning has also been shown to foster adaptation to environmental changes (Pahl-Wostl et al., 2007; Folke et al., 2003), build social trust and empower diverse stakeholders (Reed et al., 2010), by offering opportunities for groups of individuals to challenge, negotiate and propose new norms, policies or programs (Reed et al., 2010; Rist et al., 2007).

A social network's characteristics also play a significant role in the type of learning that occurs (Pahl-Wostl and Hare, 2004; Wildemeersch, 2007). These networks are not uniform and vary across space and time scales. Some networks, such as governmental hierarchies, may be inflexible and limit the degree of learning that takes place, while others, such as friendships, may be more flexible and democratic and facilitate more rapid change in personal understanding (Reed et al., 2010; Keen et al., 2005). The speed at which learning and information sharing occurs within a network (Pahl-Wostl et al., 2007; Tompkins and Adger, 2004) influences the ability of individuals to reorganize after a hazard event and therefore influences adaptive capacity. Fazey et al. (2007) state four learning-related requirements for adaptation, including: (1) the willingness to challenge and transform epistemological and cultural ways of thinking, knowledge and behaviors toward socio-ecological resilience from the individual to societal level; (2) a thorough understanding of how current practices and behaviors influence socio-ecological resilience and re-directing them toward more sustainable goals; which will support (3) the willingness to engage in proactive, continuous assessment of current behavioral impacts on sustainability, in order to inform decision-making amidst uncertainty; and (4) the ability to change their behavior based upon these requirements (Fazey et al., 2007).

Anticipatory learning that addresses adaptation is expected to increase community understanding and the ability to respond to system crises and shocks (Tschakert and Dietrich, 2010). Community disaster planning should provide opportunities for stakeholders to communicate iteratively (Osbahr, 2007), evaluate risks and adaptation options, learn from mistakes (Adger, 2003) and innovate (Armitage, 2005) amidst uncertainty, emerging events under past, present and future conditions (Nelson et al., 2007) and new information (McGray et al., 2007). The relationships between anticipatory learning, adaptation and resilience can be linked to Holling's (1986, 2004) illustrations of adaptive cycles, which identify two types of learning that may contribute to adaptation and resilience (Tschakert and Dietrich, 2010; Holling, 1986, 2004). The first consists of small and fast cycles of learning, such as immediate to midterm adaptation strategies for common and acute stressors like floods. This impacts the second type of learning, which consists of larger and slower cycles that elicit long-term social memory, legacy effects and knowledge, needed to achieve longer-term resilience and adaptation (Holling, 2004). Learning that occurs during repeated small and fast cycles is thought to cumulatively provide a new perspective on larger and slower cycles, helping stakeholders and communities better adapt to system changes, although empirical evidence to support this claim is currently lacking.

Learning is not linear, but is an iterative process with multiple feedback or ''learning loops'' (Fig. 2) that not only occurs on different temporal scales, but also differs based on the degree of reflection that occurs (Reed et al., 2010; Jones et al., 2011; Biggs et al., 2011). Single-loop learning refers to learning based on norms and beliefs that act as filters of incoming information, particularly that which does not resonate with previously held beliefs. This type of learning is thought to happen when individuals represent their knowledge at a specific moment in time (Biggs et al., 2011; Argyris, 2005). Double-loop learning includes active questioning about previously held beliefs or information, which may lead to more fundamental changes to an individual mental model (Biggs et al., 2011; Argyris, 2005) or shared through representation of group understanding (van der Wal et al., 2014) which provides an opportunity for understanding to be discussed and revised. Double-loop learning is often the minimum target of many environmental research and planning frameworks since it indicates a reflection, and potential revision, of previously held beliefs (Biggs et al., 2011). The most metacognitive form of learning is triple-loop learning, which probes underlying norms, assumptions, and values, and can result in changes in attitudes, and behaviors (Peschl, 2007; Biggs et al., 2011; Altman and Illes, 1998).

2. Participatory research approach and methods

2.1. *Mental models and fuzzy cognitive mapping (FCM)*

This research uses representations of the beliefs held by communities collected through a fuzzy-logic cognitive mapping (FCM) technique to facilitate social learning. Fuzzy cognitive maps are highly structured and parameterized versions of concept maps that represent direct and indirect causality, combining aspects of fuzzy-logic, neural networks, semantic networks and nonlinear dynamic systems (Glykas, 2010) in a stock-and-flow representation based upon individual or group beliefs (Gray et al., 2014). Because these cognitive maps are a relatively simple-to-use form of semi-quantitative modeling, they have been appropriated by a wide variety of disciplines to understand the behaviors of many complex systems (Glykas, 2010). This is because FCMs can be collected using qualitatively (e.g. low, medium, high) or quantitatively assigned weighted edges (between −1 and 1), which are easy to collect from stakeholders that can be used to define mathematical pairwise associations. Using these pairwise relationships, the structure between the concepts can be used to calculate the cumulative strength of connections between elements with weighted edges, highlighting any domain as a system. Further, FCM's can be used to develop semi-quantitative scenarios, allowing stakeholders to understand the current and projected states of systems represented with FCM (see Ozesmi and Ozesmi, 2004). Using FCM with communities to represent their collective beliefs about a particular problem allows them to: (1) represent their current understanding and learn from each other in the modeling building process (single-loop learning); (2) reflect critically on their current beliefs and assumptions (double-loop learning) after a model is constructed; and (3) run scenarios to evaluate the completeness of their previous beliefs and assumptions (triple-loop learning). Additionally, while FCMs are a popular method to understand the dynamics of many social–ecological systems (Glykas, 2010), rarely are they developed iteratively over time with stakeholders and used as a measure of conceptual change.

In this paper, we propose a conceptual framework that seeks to address the micro (short-term), meso (short-to-midterm) and macro (long-term) scales of social learning to promote change in a community's individual and group beliefs, as well as to achieve single-, double- and triple-loop learning (respectively) utilizing a 'mental modeling' exercise (Gray et al., 2013). Ultimately, this facilitates construction of measurable targets and benchmarks for community risk reduction and adaptation planning.

A novel computer-based FCM tool called Mental Modeler (Gray et al., 2013) was used during the planning process to: (1) iteratively construct and revise visual representations of stakeholders' mental models, to ultimately develop a consensus community model; (2) use these models to understand how communities anticipate being impacted by hazards; (3) define preferred targets for components of their community; and (4) model the impact of potential adaptation strategies. This approach facilitates the exploration of the dynamics and learning features of mental model representations by collecting and standardizing individual and collective community knowledge using simple modeling tasks (Ozesmi and Ozesmi, 2004; Gray et al., 2012) in a real-time and participatory modeling environment (Gray et al., 2013).

2.2. *Study location and participants*

The study took place on the North Shore of the Island of O'ahu (North Shore), a semi-rural area with tourism as the primary economic sector, followed by agriculture (DBEDT, 2011). The study area includes the communities of Mokuleia, Waialua, Haleiwa, Pupukea and Sunset Beach, up until Turtle Bay Resort (Fig. 1), an area with an estimated population of 25,000 long-term residents, transient residents, visitors and employees of

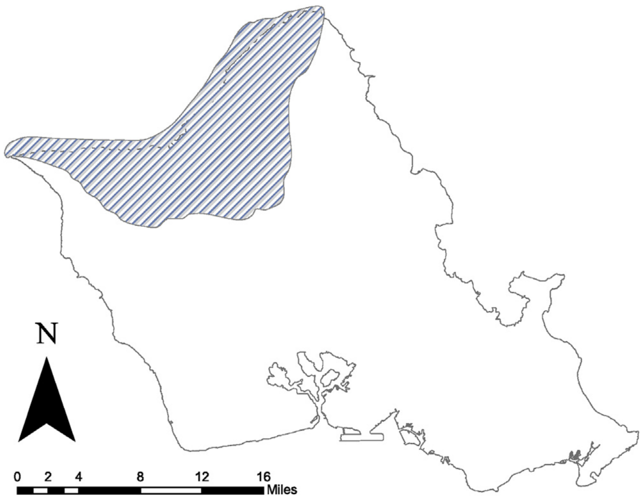

Fig. 1 – Map of North Shore, O'ahu.

local businesses at any given time (DBEDT, 2011). The North Shore is at-risk to multiple coastal hazards, and when experiencing a hazard becomes isolated, since access roads quickly become inundated. A single two-lane coastal highway provides the only entrance/exit from the area, and heavy weekend traffic is a major concern for residents. Since the North Shore is at-risk to hurricane, coastal storms, flooding, landslides and rock fall, wildfire, earthquake, and tsunami generated from earthquakes or massive landslides, originating anywhere in the Pacific Ring of Fire or the neighboring Big Island (Fletcher et al., 2002; State of Hawai'i Hazard Mitigation Plan, 2010), this road can become closed, leaving the population stranded. The North Shore was engaged as the case study site, hereafter referred to as the ''community'' or socio-ecological system of interest, via the community disaster committee, to demonstrate our planning process based on their (1) geographic isolation and physical vulnerability to natural hazards (HSCD, 2010) and climate change (DBEDT, 2011; Fletcher et al., 2002); and (2) the desire of community members and stakeholders to engage in a resilience research and planning process.

To engage the community in a local planning process, researchers collaborated with a pre-organized community-based disaster preparedness committee, which formed in 2008 following a flooding disaster event in order to raise awareness and increase community preparedness for disasters. The North Shore Community Disaster Planning Committee (hereafter referred to as *committee*) agreed to engage in a participatory modeling process to assist them with developing a community disaster plan, wherein representatives from the communities and partnering stakeholders would participate in a series of planning workshops. Four participatory mental modeling workshops were held with the committee. Workshop participation ranged from 6 to 15 people, where 10 participants attended one workshop, five participants attended two, two participants attended three, and three participants attended all four workshops. The committee had been working together over a long period of time, and made significant efforts to engage all key stakeholder groups such that the group represented a diverse cross-section of the community's diverse residents, businesses and various local, County and State organizations and institutions. The committee included community leaders, governmental emergency management departments at the County and State levels, non-governmental organizations including the American Red Cross, faith-based organizations, public health nurses, private landowners, the Port Authority, businesses via the North Shore Chamber of Commerce, and police officers. Given the committee's history and established governance structure, the committee had a well-organized electronic communication protocol that assisted in keeping everyone engaged in the process, albeit not being able to attend a particular meeting.

2.3. *Research framework*

To facilitate social learning and disaster planning in the participatory workshops, we used an FCM-based software called Mental Modeler (Gray et al., 2013), which allowed the committee to iteratively represent and revise their collective understanding throughout the process. Using an FCM approach in a three-phase process, project facilitators standardized, aggregated and revised the committee's understanding of the structure and dynamics of the community in relation to a tsunami hazard, that which the committee identified as their top concern. Each phase was designed to guide the committee through higher order learning loops (Fig. 2) across short to long-term time scales, implicating influence extending from the individual stakeholder-scale, to social network and ultimately institutional domains.

Phase I focused on project organization and a workshop targeting short-term single-loop learning of individual stakeholders of the committee, through the development of two small group shared models of their community. Phase II included merging the small group mental model representations, building consensus on the structure and dynamics of their community, and understanding the potential impacts of tsunami in order to target double-loop learning within the social network domain of influence. Through running iterative scenarios representing the anticipated impacts of a tsunami, compared with potential impacts under proposed adaptation strategies, Phase III enabled institutional-level processes through challenging local to State-level plans and protocols influencing tsunami risk, eliciting triple-loop, longer-term learning. The four most effective adaptation strategies for achieving disaster-planning targets were examined more closely by the committee and developed into an implementable action plan, including benchmarks for monitoring and evaluation.

2.4. *Phase I: small group modeling and single-loop learning*

Occurring in the micro time scale of social learning, the first phase focused on consensus-building with the committee around community adaptation planning procedures, methods and goals, representing their current understanding of their community socio-ecological dynamics. These included social, political, cultural, environmental, institutional, physical and environmental components and the influential relationships

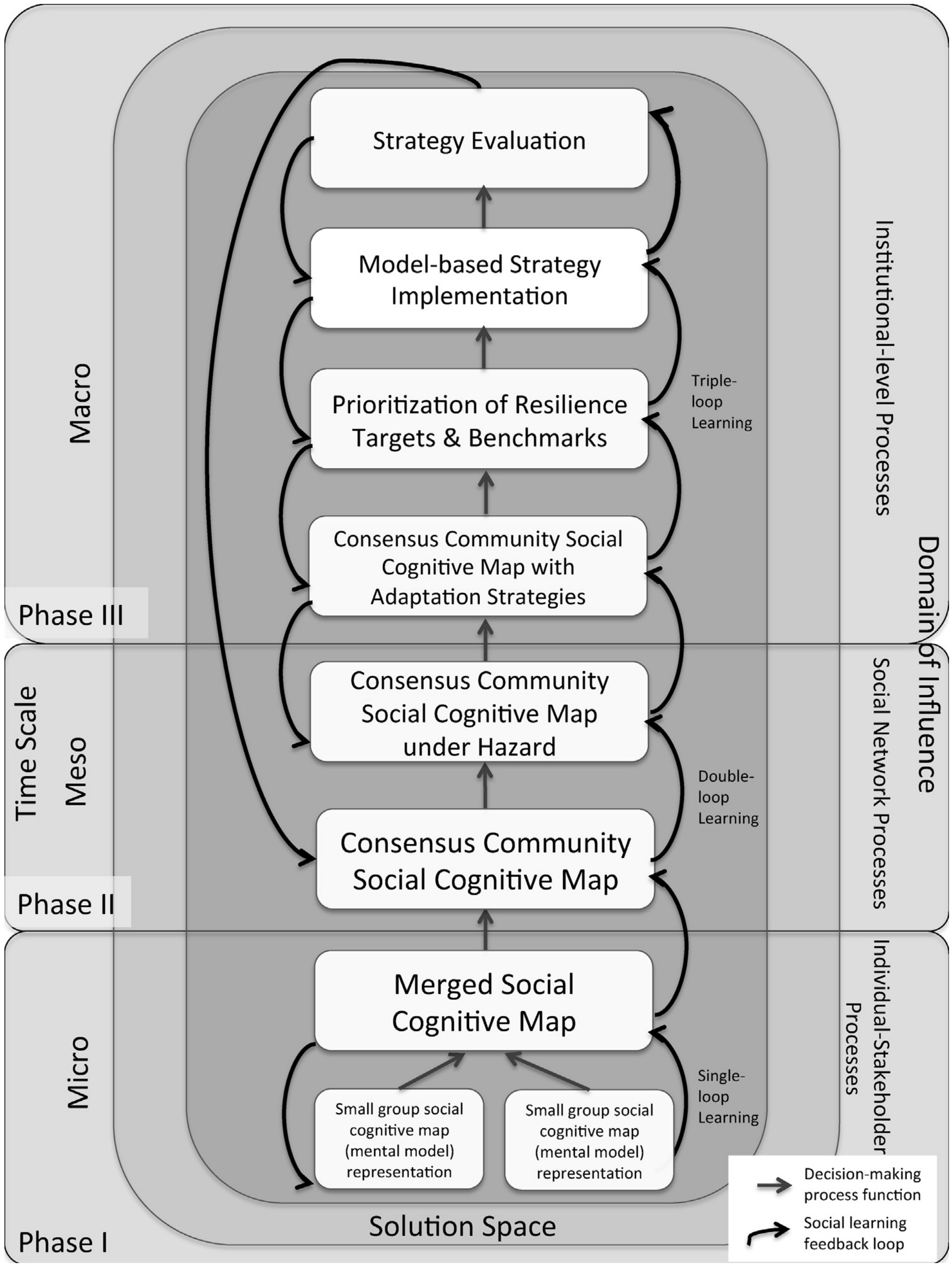

Fig. 2 – Conceptual planning and social learning framework.

between them. The first workshop consisted of dividing the committee into two small groups of 7 and 8, respectively, representing diverse community, governmental and institutional constituents. These small groups were charged with developing fuzzy-logic cognitive maps of their community based on their current beliefs, expertise and experiences. To facilitate this, the two small groups completed the following activities: (1) brainstormed the key components, assets and resources that group members' perceived to comprise their community system; and (2) defined the dynamic and networked relationship between these components, in terms of their direction (unidirectional or bidirectional) and degree (low, medium, or high) of positive or negative influence between components.

To develop their models, community members used the Mental Modeler software (www.mentalmodeler.org), which facilitates the FCM process, allowing components and the relationships between components to be defined based on automated FCM parameters. Qualitative symbologies of positive (+), negative (–) and neutral (0) (no influence between concepts) relationships are thus translated by the software into quantitative values, varying from low (0.25), medium (0.5) and high (1.0). These components and their relationships were considered to represent the small group's understanding of their community's dynamics at the start of the planning process.

Fig. 3 represents a FCM constructed using Mental Modeler for one small group. The blue lines indicate positive relationships

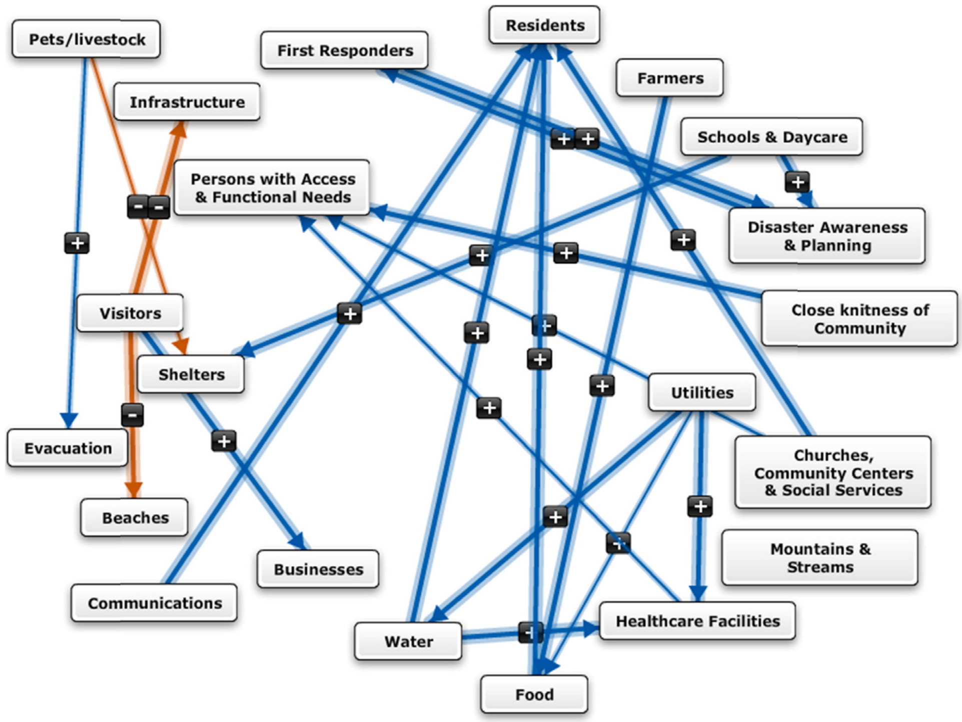

Fig. 3 – FCM collected from one small group. (For interpretation of the references to color in the text citation to this figure, the reader is referred to the web version of the article.)

and the red lines indicate negative relationships, with arrows indicating directionality of the component influencing the other. Line thickness indicates the strength of relationships between variables, with thicker lines indicating stronger relationships. For example, the component "Pets/livestock" influenced the component "Evacuation," such that this component increases jointly with "Evacuation." However, "Evacuation" increasing is not expected to increase "Pets/livestock." In other cases, the influence runs in both directions, as is the case with "First Responders" and "Disaster awareness and planning." Thus, individuals were presented with new ideas from various members, challenging individual mental models or understandings of community. This initial phase generated much discussion as the group debated the community system model and definitions of its components, resulting in first-order (e.g. single-loop learning) understanding of their community dynamics (Biggs et al., 2011; Argyris, 2005).

In between the first and second workshop, the two small group mental model representations were merged into one by constructing an adjacency matrix (Ozesmi and Ozesmi, 2004; Laszlo et al., 1996; Kosko, 1987, 1992a,b) using a mean approach, averaging values for common components and relationships, sometimes referred to as a "social cognitive map" (Ozesmi and Ozesmi, 2004). Merging the two group models into a single model was done in order to create a representation of community dynamics that included both groups' beliefs and relationships (e.g. a positive value in one small group model and a negative value in the other decreased the strength of the causal relationship, whereas agreement reinforced it) (Kosko, 1992a,b). For example, one small group purported that the impact of the number of visitors would have a low negative influence on the component "Communications and Logistics Demand" whereas the other small group indicated a high positive influence; this conflicting valuation decreased the strength of the causal relationship to be a low positive influence, whereas agreement on the influence of the component "# of First Responders" was indicated to have a high positive influence on "Disaster Awareness and Planning" in both small groups, the resulting consensus value was thus a reinforced high positive value. This provided a representation of the knowledge shared by both small groups, to be used for revision and debate about the structure and dynamics of the model of their community.

2.5. *Phase II: consensus modeling and double-loop learning*

Taking place in the meso-scale, the second workshop was designed to enable the committee, then participating as a single larger group, to evaluate a representation of the combined knowledge of the two groups, and use this model as artifact for discussion and revision of their ideas, in order to produce a singular model that represented consensus among committee members. To facilitate this, participants evaluated the social cognitive map produced by the two groups during the second workshop. All of the concepts included by combining the first two models were evaluated individually, until a final list of components was agreed upon. Secondly, all relationships and their degree of influence between components were evaluated until overall agreement was reached

(Fig. 4). As the entire committee continued to examine the merged community model, and later refined it as the consensus community model under tsunami, the active questioning of the groups' understanding of the community system led to changes to the committee's shared representation of the group's understanding. According to Biggs et al. (2011) and Argyris (2005), this indicates that double-loop learning has occurred, as the initial community model representation was altered to become a new representation of knowledge distinct from the committee's understanding at the onset of the planning process.

2.6. *Phase III: scenario modeling and triple-loop learning*

At the end of the second workshop following the consensus model development, the committee structurally added the hazard tsunami to their community model, identifying the direct relationships and the degree of influence that a tsunami might have on the components included in the consensus model. This allowed for the impact of a tsunami to be calculated using the FCM scenarios (Ozesmi and Ozesmi, 2004) constructed using Mental Modeler (Gray et al., 2013), in order to illustrate how a tsunami might affect each component either directly or indirectly based on the dynamics defined in the consensus model. Thus, the total impacts of a tsunami, as represented by the relative change in each component in the community system, could be examined in the third workshop.

The third workshop began with a review of the tsunami scenarios results, along with a discussion of potential strategies that might prevent (avoid), mitigate or enable adaptation around the unwanted outcomes. Collectively, the committee generated four distinct adaptation strategies (Table 2), which were added as components and structurally related to the consensus model. Adding each strategy to the model defined the perceived manner in which each strategy was anticipated to relate to the functional dynamics of the community. Next, scenarios were again run, which included evaluating the relative impact of each adaptation strategy in relation to the tsunami scenario (Fig. 5).

Finally, a fourth workshop was conducted to review these scenario outcomes, in order to quantify the efficacy of the proposed adaptation strategies in achieving the desired results and addressing the underlying root causes of vulnerability. The committee categorized their preferences for a change in value for each concept included in the consensus model as *desirable to increase*, *desirable to decrease* or *no preference* (Tables 2 and 3), in order to better evaluate the scenario results (Fig. 5). The committee discussed the output for each strategy, focusing on the potential underlying causes of the negative impacts. The indirect relationships, which were not anticipated by committee members, resulted in a more thorough examination of each strategy.

3. Results

3.1. *Phase I: small group modeling and single-loop learning*

Evidence of the conceptual change that occurred as individuals learned from each other, is based on comparing the structural metrics in the small group, merged and consensus models (Table 1). Workshop 1 facilitated the building of two small group models representing the understanding of the community as they began the planning process. These models included 24 and 23 concepts with 60 and 65 relationships defined, respectively. Following Workshop 1, these models were merged into a common model, with 23 components and 75 connections, which was utilized as an artifact for discussion and further revision to yield a consensus model (Workshop 2) with 20 concepts and 57 connections. When the structure of the two small group models are compared to the structure of the merged model and the following consensus model, group knowledge about the major concepts and connection between concepts was refined, since the

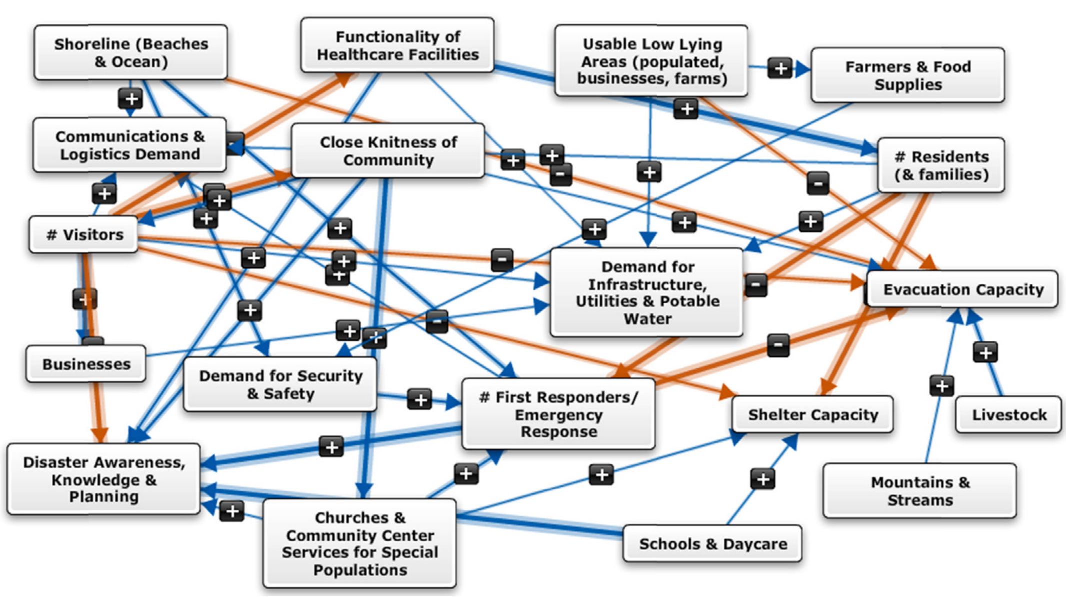

Fig. 4 – Community consensus model collected from the community.

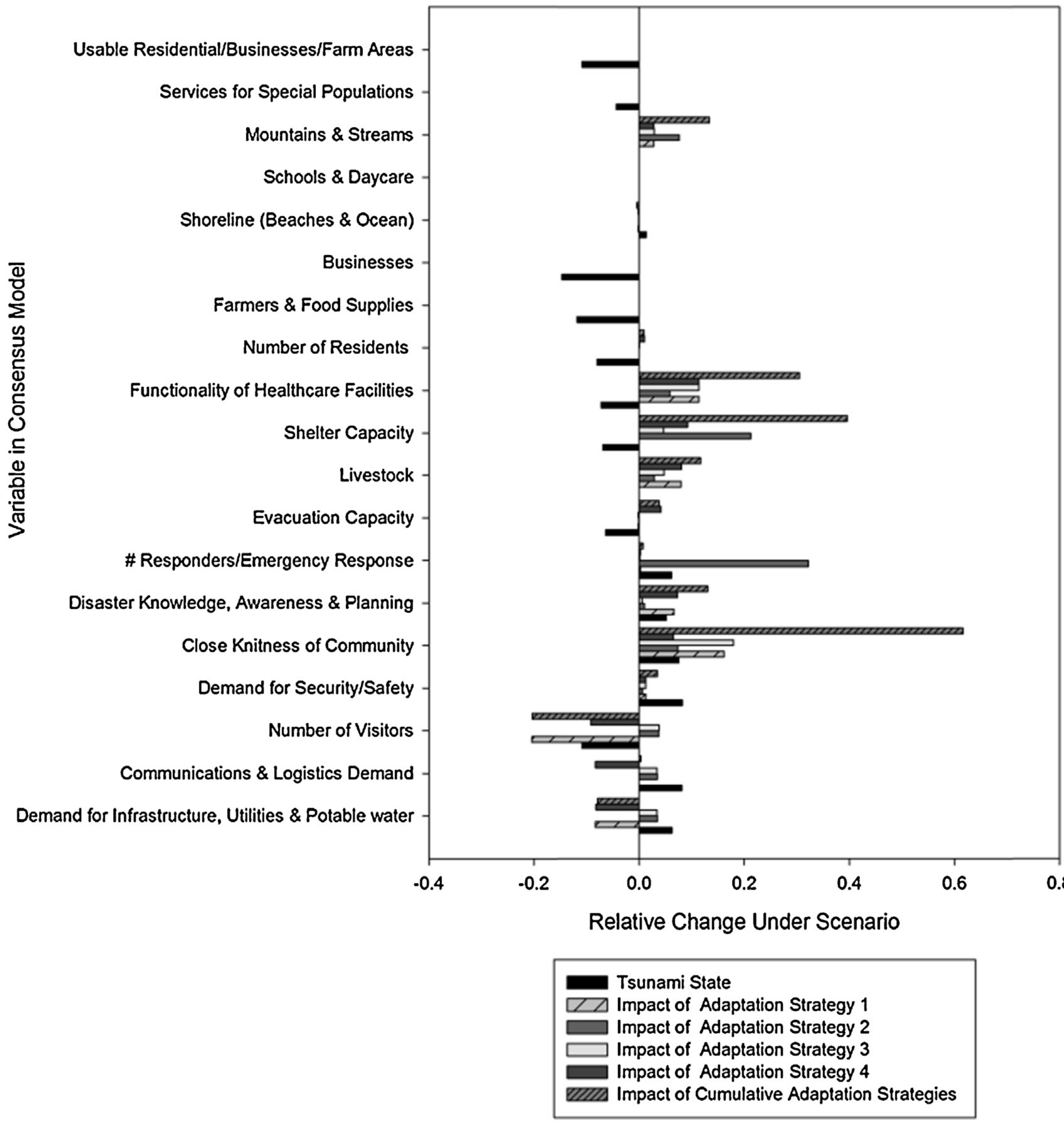

Fig. 5 – Relative impact of tsunami with and without adaptation strategies.

number of concepts included in the model was reduced through deliberation (from 24 to 23, and finally 20), along with refinement of the number of connections (from 75 to 57) due in part to the reduction in the number of components. This provides evidence that individuals reflected upon their beliefs of the community system, learned from each other over participatory discussions of the model iterations, improved their understanding of their community system. This is therefore proposed as evidence of single-loop learning among workshop participants (Reed et al., 2010; Fazey et al., 2007).

The number of connections to the number of variables or connections represented measures the degree of connectedness between concepts, which increased from 2.5 and 2.826 in the first workshop small group models, to 3.261 in the merged model, and 2.85 in the consensus model, again likely due to the decrease in the total number of components and the connections between them. These progressive changes in model metrics indicate that collaboration and knowledge-sharing resulted in a more connected perception and understanding of the system, illustrating social learning (Reed et al., 2010; Fazey et al., 2007) and provide evidence that single-loop and double-loop learning occurred.

In addition, each concept included in the model can be categorized as a transmitter variable (arrow only defined outward from concepts with no directed relationships flowing into variables), receiver variable (arrow only defined inward toward a concept with no directed relationships flowing out from a variable) or ordinary variable (arrow flowing into and out from a variable). The relationship between transmitter and receiving variables provides a ‘‘complexity score’’ (Ozesmi and Ozesmi, 2004; Gray et al., 2014) for models, which signifies whether systems are perceived to be less complex when many transmitters are represented with only a few outcomes (receiver variables) of those pressures represented. The

Table 1 – Structural metrics of the small group models, merged model and community consensus model, under tsunami only.

Structural metric	Small group A model	Small group B model	Merged model	Community consensus model-tsunami
Number of components	24	23	23	20
Number of connections	60	65	75	57
Connections/variables	2.5	2.826	3.261	2.85
Number of transmitters	3	10	9	10
Number of receivers	7	13	4	0
Number of ordinary	14	0	10	10
Complexity (transmitters to receivers)	2.333	1.3	0.444	0
Density (# connections/total # of possible connections)	0.042	0.044	0.043	0.1425

structural metrics indicate that a more complex model was developed by group A compared to group B, however, group A's model was less dense and had fewer connections. When these small group model values are compared to the consensus model, as the latter resulted from collaboration, discussion and an amalgamation of the individual strengths of the two small group models, we observed an increase in the number of connections per variable (a strength of the group B's model), similar density, and reduced complexity (a strength of group A's model). The latter is due to the fact that complexity (as defined in prior literature) here is merely a function of transmitters to receivers, when the latter in the consensus model was a value of 0, and consequently the complexity score was thus also 0. This is most likely due to the model no longer including receiver components but only either transmitter or ordinary component, which could in fact be a sign of a complex model that shows significant interlinkages and influences between system components. These changes in the structural metrics of the model demonstrate that individual committee members examined and reflected upon their personal beliefs and mental models, indicating achievement of single-loop learning (Reed et al., 2010; Jones et al., 2011; Biggs et al., 2011).

3.2. *Phase II: consensus modeling and double-loop learning*

After the committee agreed on the components and relationships in the consensus model in the second workshop, the hazard tsunami was structurally added to the model. Fifteen relationships were defined that linked tsunami with other components. In addition to defining the structural relationship between the tsunami and community dynamics, the community also defined a set of optimal outcomes in terms of the desired state of their community by indicating if they preferred that the components included in the model increased, decreased or remained neutral with no preference. Of the 19 components included in the consensus model, the committee preferred that ten increase, four decrease, and they had no preference for change in five components (Table 3).

The process of revising the model together promoted considerable discussion and resulted in double-loop learning among participants, with different committee group members contributing different experiences and expertise within different components of the model. They represented the perspective of various stakeholders' social networks in the community and the outlook of larger institutions based outside of the community, in order to support double- and triple-loop learning, respectively (Biggs et al., 2011; Argyris, 2005). The model output of the impacts of tsunami (Fig. 5) enlightened the committee members' previously held beliefs about the community's risk to tsunami, changed their awareness and increased overall understanding of the model dynamics and particular components at greater risk. Biggs et al. (2011) and Argyris (2005) define this as double- and triple-loop learning.

3.3. *Phase III: scenario modeling and triple-loop learning*

After structurally relating the tsunami to the consensus model and defining the desired influence of the adaptation strategies on the community in the third workshop, the committee structurally related potential adaptation strategies to the model (Fig. 5). Less than half of the consensus model components were directly connected to the proposed strategies; anticipated direct influences of each adaptation strategy on the consensus model components were discussed and estimated (Table 2). These preferences serve as the committee's adaptation strategy benchmark targets to reduce undesirable impacts from tsunami, which were applied to the model under the tsunami scenario state.

For the fourth and final workshop, the tsunami scenario was then used to investigate whether the anticipated positive, negative, and neutral influences of each adaptation strategy, including the cumulative strategy state, were achieved (Y = 1) or not (N = 0) under tsunami (Table 3).

The relevance of the influence of each adaptation strategy upon particular components in the committee's tsunami mental model representation is driven by the committee's identification of which components they desire to increase (i.e. shelter capacity), decrease (i.e. communications and logistics demand) or remain unchanged or neutral (i.e. schools). Table 4 highlights which strategies were most effective at achieving the desired impacts, both direct (Table 2) and indirect, due to the dynamic interconnected nature of the consensus model. The most effective adaptation strategy, achieving 100% of the direct desired changes and 78% of the total desired changes, was Strategy 4.0: increasing communitywide disaster preparedness education and training. Strategy 5.0, the cumulative state of all four strategies, did not exhibit the highest percent of desired change, potentially due to unanticipated cumulative direct and indirect dynamic influences.

Table 2 – Adaptation strategy influences on consensus model components.

Adaptation strategy	Consensus model components and direct preferences									
	Desirable (to increase)						Neutral (to maintain)	Undesirable (to decrease)		
	Evacuation capacity	# Responders/ emergency response	Functionality of healthcare facilities	Disaster knowledge, awareness and planning	Shelter capacity	Close knitness of community	Churches and community center services for special populations	Communications and logistics demand	Demand for infrastructure, utilities and potable water	Demand for security/ safety
1.0 Build leadership capacity in community	1	0.5	0	1	0	0.5	0	−0.5	0	−1
2.0 # Shelters and shelter volunteers increased	0.5	0	0	0.25	1	0.25	0.25	0.25	0.25	0.25
3.0 Increase # evacuation routes, protocols and public awareness	1	0	0	0.5	0.25	0.5	0	0.25	0.25	0.25
4.0 Increase # of people trained in disaster preparedness	0.5	0.5	0.25	1	0.5	0.5	0	−0.5	−0.5	−0.5

Table 3 – The effectiveness of adaptation strategies on the committee's tsunami mental model representation.

Consensus model components	Community defined outcomes	Desired change achieved (Y = 1, N = 0)				
		Adaptation strategy 1	Adaptation strategy 2	Adaptation strategy 3	Adaptation strategy 4	Cumulative adaptation strategies
Demand for infrastructure, utilities and potable water	–	1	0	0	1	1
Communications and logistics demand	–	0	0	0	1	0
# Visitors	–	1	0	0	1	1
Demand for security/safety	–	0	0	0	0	0
Close knitness of community	+	1	1	1	1	1
Disaster knowledge, awareness and planning	+	1	1	1	1	1
# Responders/emergency response	+	1	1	1	1	1
Evacuation capacity	+	0	0	0	1	1
Livestock	+	1	1	1	1	1
Shelter capacity	+	1	1	1	1	1
Functionality of healthcare facilities	+	1	1	1	1	1
# Residents (and families)	+	0	0	1	1	1
Farmers and food supplies	+	0	0	0	0	0
Businesses	+	0	0	0	0	0
Shoreline (beaches and ocean)	No change	0	0	0	0	1
Schools (and daycare)	No change	1	1	1	1	0
Mountains and streams	No change	0	0	0	0	0
Services for special populations	No change	1	1	1	1	1
Usable low lying areas (residential/businesses/farms)	No change	1	1	1	1	1

Table 4 – Percent desired changes across all strategies.

	Mitigation/Adaptation Strategy	% Direct Desired Impacts Achieved	% Total Desired Impacts Achieved
1.0	Build leadership capacity in community	100%	67%
2.0	# Shelters and Shelter volunteers increased	50%	44%
3.0	Increase # evacuation routes, protocols and public awareness	57%	56%
4.0	Increase # of people trained in disaster preparedness	100%	78%
5.0	All Strategies	80%	56%

All strategies had a greater success rate of achieving direct versus total desired impacts, due to explicit less desirable influences of specific components. The committee was not able to account for the indirect effects without using FCM. Committee members felt they knew which adaptation strategies would be most effective a priori based on their own knowledge and their expectations did not prove correct. The information provided by the model could not be ignored because they built the model themselves. They also felt more empowered to explore other options because they had learned FCM is very useful for evaluating options in a more participatory and quantitative, objective manner.

This process facilitated discussion around potential reasons for why particular strategies were more or less successful at achieving desired results, both directly and indirectly. In particular, discussion centered on the committee stakeholders' behaviors, attitudes, norms and values that contribute to these root causes of relationships and influences, illustrating triple-loop learning (Peschl, 2007; Biggs et al., 2011; Altman and Illes, 1998). The adaptation strategies were developed into a disaster action plan, through identification and implementation of policy and programmatic targets, and evaluative benchmarks which address these underlying dynamics and root causes of vulnerability through engaging stakeholders, over time, across the domains of influence from the individual, social network and government to institutional levels (Fig. 2). This outcome supports the conclusion that single-, double- and triple-loop social learning occurred (Biggs et al., 2011)

4. Discussion

Three different levels of social learning occurred through iterative modeling, identification of anticipated impacts of a tsunami, and identification of adaptation strategy efficacy via scenario results using software that facilitated the process. Individual reflection demonstrated single-loop learning, and group discussion demonstrated double- and triple-loop learning around: (1) potential reasons for the varying success of different strategies at achieving the desired results; and (2) iterative revision of the disaster action plan based on the new awareness, understanding and knowledge generated. Monitoring, evaluation and revision of these strategies, the action-oriented targets and evaluative benchmarks, will be facilitated in future committee workshops by revisiting the scenario output and identifying whether the anticipated increase in adaptive capacity occurred over longer time scales.

The committee's model representations allowed the group to engage in consensus-building via complex systems scenario analysis, which is expected to increase anticipatory social learning and adaptive capacity (van der Wal et al., 2014). The findings support selection of strategies perceived to be more "effective" in terms of moving the community toward a preferred state and away from an undesired state, perceived based on the tsunami scenario results. Based on changes to the structure of their model (Table 1) and their ability to anticipate and define more or less desired states of their community under the tsunami results in comparison to their potential adaptation plans (Table 3), we contend that the committee's original beliefs that the strategies would not impact the entire consensus model were challenged by results that revealed unintended indirect negative outcomes. For example, Strategy 3.0 was primarily linked to increasing evacuation capacity, functionality of healthcare facilities, close knitness of community and shelter capacity, however this strategy also increased the demand for communications and logistics, infrastructure and safety and security, which is an undesirable outcome. The undesirable outcomes were often linked with indirect effects that were difficult for the committee to anticipate until the process facilitated the analysis. The research framework facilitated the committee's transition from qualitative thinking about the community model and an adaptation strategy's potential impacts, to agreement on the quantitative measures, in order to produce the scenario output. The committee deliberated and modified the targets and benchmarks of each strategy as they examined the scenario-driven indirect effects, which provides additional evidence that triple-loop learning occurred. All of the strategies require participation and cooperation from the various organizations, government agencies, community entities and social networks represented by the committee stakeholders, which will extend the social learning beyond the committee network (Reed et al., 2010) and into the institutional, social and cultural domain of influence (Biggs et al., 2011; Rodela, 2011).

Pros and cons to engaging individuals, small groups or large collectives in modeling exist. The method presented here combined the FCMs of small groups into a merged and ultimately consensus representation, and allowed for components to be freely chosen and debated by participants. This participatory approach facilitates social learning (Reed et al., 2010; Rodela, 2011), the pooling of diverse knowledge sets, real-time modification of the model through discussions and consensus-building (Gray et al., 2014), and time and resource efficiency through selection and implementation of scenario-tested adaptation strategies (van der Wal et al., 2014). Constraints of this approach include the need for diverse expertise, the inability to weight individual components or relationships, and the issues inherent with varying power dynamics in groups that require expert facilitation. Issues with having different stakeholders participate during each phase may also affect the process, if continued revision of the model occurs. Mental Modeler was revised after it was used in this participatory planning effort to allow users to record notes about the components and the connections. This allows users to understand, track and alter the rational behind the model.

Mental model representations and processes are dependent upon the value, quality and diversity of information put into the model. Construction of mental models in small groups is time consuming, and building consensus around complex community socio-ecological systems, particularly under scenarios of uncertainty-driven disturbances like tsunami and other hazards, can be daunting. Evaluation of the learning processes and action plan benchmarks through surveys and FCM outcomes over time will validate whether adaptive capacity will increase.

Community mental models are dynamic and must be revisited as the community undergoes change, learns from past experiences and confronts new challenges (Ozesmi and Ozesmi, 2004). Utilizing FCM for decision-making enables improved governance (van der Wal et al., 2014), more efficient prioritization and implementation of funding, human resources and adaptation strategies (Biggs et al., 2011). Decision-making may be supplemented in a variety of ways, including the use of Analytic Hierarchy Processes, Analytic Network Process (Saaty, 2001) or Cost–Benefit Analyses (Campbell and Brown, 2003), in order to constructively weigh and deliberate which solutions are ideal, given manpower, time and funding resource constraints. FCM will be continuously utilized for Phase 3 monitoring and evaluation by the committee, to support the committee's achievement of their overall goal of increasing adaptive capacity and fostering community resilience through informed disaster planning (van der Wal et al., 2014).

5. Conclusions

This research used a structured framework that incorporated FCM to guide community stakeholders on the North Shore of the Hawaiian island of O'ahu, through single-, double- and triple-loop social learning cycles, in order to increase expected adaptive capacity across individual, social network and broader institutional domains of influence. The use of FCMs facilitated explicit representation of stakeholder group cognitive maps, which served as the basis for identifying perceived risks, assets, values and dynamics of the social, economic, environmental and political aspects of North Shore. Deliberation over anticipated impacts of tsunami and proposed mitigation and adaptation solutions was informed through FCM scenario output. Facilitation of this process requires great care in promoting creative and sensitive discussions within the solution space, while continuously guiding the community committee through the structured project phases. The framework and process provide a template that is best used when adapted and modified over time, and may be amenable for decision-making and planning in other communities, applied to a variety of planning initiatives (e.g. disaster planning, climate change adaptation, and resource management, etc.) amongst diverse multiparty groups or organizations.

The use of the Mental Modeler software, which allowed the planning committee to examine various adaptation strategies and determine their impacts as a group, facilitated the committee's social learning process. The uncertainty faced by the committee as they strived to increase adaptive capacity became more manageable, as they were able to agree on quantified relationships that measured how various strategies reduce the risks they face. Iterative participatory modeling and evaluating change in mental model representations can serve as empirical evidence of social learning, and are particularly useful in community disaster planning and adaptation.

Acknowledgements

The authors would particularly like to thank the communities and stakeholders of the North Shore, O'ahu disaster committee for their time, commitment and insight throughout this research and planning project. This effort was partially supported by Hatch and Smith-Lever funds from the USDA National Institute for Food and Agriculture Project No. 131H, administered by the College of Tropical Agriculture and Human Resources, University of Hawai'i @ Mānoa, and by the National Oceanic and Atmospheric Administration, Coastal Resilience Networks Program Award NA12NOS4730192 administered by the Pacific Services Center.

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