Supplementary Material

# Supplementary Text

Salience of a model is multi-faceted. Elements of salience are derived from model relevance

(i.e., is the information useful for responding to the problem) (Wilson 2009). Further, the context of knowledge is key in determining model salience; if stakeholders don’t see the model as important for “understanding and solving the policy issue at hand” (i.e., they have to know that it is relevant), then the model lacks salience (van Voorn et al. 2016 p. 225). The credibility of the model concerns the logic and soundness of the model’s construction and output (van Voorn et al. 2016). When considering model credibility, stakeholders will evaluate if the model concepts and processes are technically adequate and meet their standards for a reliable representation of the system. Lastly, the legitimacy of the model stems from the stakeholders’ perception of the model fairness and its use in decision making (Cash et al. 2003, Wilson 2009, White et al. 2010). Legitimacy of the model will be determined by each stakeholder’s belief about what constitutes fairness (Wilson 2009). Using this SCL analytical framework, we can measure stakeholder’s attitudes towards models

during a participatory modeling process. Some work has been done to understand process impacts on

participants (Pahl-Wostl 2002, Rouwette et al. 2002, 2011). Even more limited has been attempts to

understand longitudinal changes in stakeholders due to these processes (Rouwette et al. 2002, 2011).

Factors Impacting the Formation of Attitudes - The Role of the Participatory Process and Social Network factors

Research into how individuals form their attitudes spans many disciplines, ranging from marketing (Bottomley and Doyle 1996), to psychology (Addison and Thorpe 2004), education (Stenseth et al. 2016), and issues of climate change and individuals’ connection to nature (Happer and Philo 2016). Within a participatory modeling process, the study of attitudes can provide insight into the impact or effectiveness of these processes overall and the tools, like models, they utilize. Interest, concern or worry surrounding a topic, like scientific modeling, can led to an active response by way of behavioral changes (Moser and Dilling 2010). Some work has examined the impact of group model building and the overall process on attitudes (Rouwette et al. 2011). No work, however, has examined attitude formation in relation to the models themselves. Studying attitudes towards models is crucial to understanding what role models play within participatory modeling processes and if these processes can accomplish their goals (i.e., consensus). To determine what impacts changes in attitudes towards models, we focused on factors related to the participatory process itself and the stakeholders’ social network.

Participatory Modeling Process Design and Stakeholder Characteristics – Impact on Attitudes Towards Models

Despite the diversity in the design and organization of participatory modeling processes (Reed 2008, Voinov and Gaddis 2008, Falconi and Palmer 2017), there exist some universal factors that can be used to broadly understand their impact on stakeholders’ attitudes towards models. By investigating what factors of participatory modeling practices influence stakeholder’s attitudes towards models and *how*, we can better understand the role that the scientific models play during participatory modeling processes.

The selection of stakeholders and the representativeness of different stakeholder groups is a critical element of participatory modeling processes. The literature emphasizes the importance of who sits around the table, suggesting that individual characteristics and overall group composition can have a meaningful influence on group dynamics, model goals, formation and presentation, and the individuals themselves (Reed 2008, Voinov et al. 2014). The group of participating stakeholders dictates the knowledge available to the process. In terms of the model and impacts on the process overall, increasing the diversity of knowledge sources could enhance the ability of the model to represent the system in question by accounting for multiple perspectives (Duncan 2016). However, within the larger group, there exist natural sub-groups representing the different stakeholder groups within the process. These sub-groups represent pockets of knowledge and information. The availability of this group-specific information to the overall group has been suggested to foster innovation in decision-making processes (Fischer and Jasny 2017).

Individuals within the same stakeholder sub-group have similar life experiences that facilitate increased communication and ease the development of trust (Yuan and Gay 2006). Oftentimes this results in individuals reflecting and reinforcing the views of their sub-group, leading to the creation and reinforcement of echo-chambers of group-specific attitudes (Long et al. 2013). Paolisso and Dery (2010) noted differences in opinions on management options for oysters within the Chesapeake Bay based on stakeholder group affiliation. The increased level of familiarity and understanding with those in the same stakeholder sub-group can influence attitude formation.

Individual-level stakeholder characteristics other than sub-group membership can also impact attitudes. Along with ones’ sub-group association, years of experience speaks to different ways of knowing among stakeholders (Lejano and Ingram 2009). Learning and understanding begin with what individuals “already know and have experienced in everyday life” (Barnhardt and Kawagley 2005 p. 12). Different amounts of experience in one’s field influences how stakeholders see and experience the world, including their assessment of the validity of knowledge, how knowledge is produced, and the assumptions inherent in the production of knowledge (Miller et al. 2008).

Since the early 2000’s, scientific models have become much more common in natural resource management (Shenk and Franklin 2001). During this time period, stakeholders involved with or exposed to natural resources management decisions are therefore necessarily interacting with scientific models. Stakeholders’ views on models could be impacted by different familiarity with scientific models and years of experience within their field. For example, stakeholders with more experience are likely more familiar with the benefits and limitations of models within natural resources management (e.g., when it is or is not appropriate to use models). However, different ways of knowing inherent within different stakeholder sub-groups (e.g., watermen’s experiential way of knowing versus scientists’ more standardized, quantifiable way of knowing) could lead to inter-group differences in attitudes (Berkes 2009, Duncan 2016).

The literature also emphasizes the impact of stakeholder participation during participatory modeling processes. Different levels or degrees of participation, whether through process design or stakeholder attendance, has been cited as influencing the process itself and the results (Reed 2008). Increased participation can lead to the development of shared concepts and ideas through social learning, promoting the likelihood of actors continuing to work together (Reed 2008, Scholz et al. 2014). The inclusion of models in the participatory process is thought to further enhance these positive results. Participation in participatory modeling processes takes place through model building. The model acts as a boundary object (White et al. 2010, Henly-Shepard et al. 2015), helping to facilitate the discussion between stakeholders, allowing them to better recognize their implicit assumptions (Andersen et al. 1997), refine and alter their mental models (Rouwette et al. 2011), and generalize knowledge that can be used or applied later or in a different scenario (Lane 1994). Through experience with model building, stakeholders can better understand the strengths and limitations of the model for decision-making.

However, the theorized positive impacts from participation and engagement in participatory processes aren’t universal (Layzer 2008, Newig and Fritsch 2009). For participatory modeling processes, their ability to deliver on these results rests on stakeholder’s willingness to use and engage with the model. This willingness can be examined through the salience, credibility, and legitimacy framework (van Voorn et al. 2016).

A Social Network Approach to Attitude Formation

Network literature has long argued that “attitudes are made, maintained, or modified” through interpersonal relationships and communication (Festinger 1954, Visser and Mirabile 2004, Erickson 1988, p. 99). Thus, to understand and describe how attitudes are formed, social networks are the “natural units of analysis” (Erickson 1988, p. 99). The relationships and interactions between the stakeholders involved in participatory modeling processes represent “networks” that can be formalized through a social network analysis approach (van der Hulst 2009). The application of a social network analysis framework to study participatory processes has been limited (Prell et al. 2009) and hasn’t been applied to a modeling process or longitudinally. Through the analysis of overall network structure and specific stakeholder roles during participatory modeling processes, we can better understand how the connections between actors during this process could impact the formation of their attitudes towards models. Specifically, brokerage roles within networks and overall levels of connectivity are examined to understand the impact of social network structure on attitude formation.

Brokerage in Communication Networks

Brokers are individuals in a network that facilitate a transaction between two otherwise unconnected actors (Marsden 1982). This position is seen as powerful; brokers can control how information flows within a network, facilitating opportunities for interaction, or inhibiting the spread of knowledge and resources (Cvitanovic et al. 2017). The role brokers play is considered especially advantageous in networks with many isolated clusters or sub-groups, like participatory decision-making processes. Sub-groups in networks represent silos of knowledge and information that, if left unconnected, cannot benefit the overall network (Long et al. 2013). In these settings, brokers have the unique ability to create connections to these divergent sources of knowledge, breaking down silos and opening room for greater collaboration, innovation and understanding (Padula 2008, Long et al. 2013). All brokers, however, are not made the same. Gould and Fernandez (1989) used an ego-centric (an individual-focused) approach to divide the concept of brokerage into five distinct roles based on *who* the individual is brokering communication between. Two roles, gatekeeper and liaison, could impact attitude formation towards scientific models.

Breaking Down Brokerage: Gatekeepers and Liaisons

A gatekeeper is an individual who, in an un-directed network, acts as the access point to their sub-group. These brokers represent the only path of connection in a network between their sub-group and an individual in a different sub-group (Figure 1).



**Figure 1**: Representation of a Gatekeeper brokerage role (B), where B and C are members of the same sub-group, and B acts as the only path of communication between A and C. In this position, B can decide whether to grant access to the outside information into the sub-group

From this intermediary position, gatekeepers can selectively grant access to and from their group, acting as a gate that either permits or hinders the spreading of information (Gould and Fernandez 1989). Limitations in awareness and availability of information has been noted as an important factor in attitude formation (Upham et al. 2009). By controlling this flow, gatekeepers can influence attitude development. A liaison represents a brokerage role where an actor links two different sub-groups, neither of which they are a member (Figure 2, Gould and Fernandez 1989). The liaison mediates and coordinates transactions, playing a key role in connecting otherwise disconnected groups. This type of brokering creates more points of access to different sources of information and individuals, again potentially impacting attitude formation.



**Figure 2**: Representation of a Liaison brokerage role (B), where A, B, and C are all members of separate sub-groups. B’s role here is to provide a link between individuals in two different sub-groups, while not being a member of either group

While there are potential attitude impacts network-wide or within a specific sub-group from these positions, brokers themselves can be impacted by their roles. Valente and Fujimoto (2010) suggested that individuals in these brokering roles are more receptive to attitude changes because they are the recipient of targeted communication. These brokers are being sought out for communication, which can have a more substantial influence on attitude formation. Brokers also have access to an expanded range of ways of knowing. Through connections beyond one stakeholder sub-group, brokers’ attitudes towards models may be influenced, depending on the nature of those connections (Beach 1997, Hargadon 2002).

Degree Centrality

The theory of brokerage posits that actors are influenced by the specific nature of their connections; it’s not just how many people you know, but *who* you know. Conversely, the idea of degree centrality focuses on that concept of ‘how many’ people you know. The degree measure is the total number of nodes that an actor is connected to (Opsahl et al. 2010). Individuals with high degree scores are in prominent and visible positions within the network. Rogers (2003) found these high degree individuals to be opinion leaders. The nature of this leadership position can come with an expectation to uphold the status quo, limiting any changes in these actors’ attitudes (Becker 1970, Valente and Fujimoto 2010).

The OysterFutures Case

OysterFutures was the participatory modeling setting in which we studied the longitudinal changes in stakeholders’ salience, credibility, and legitimacy attitudes towards scientific models. Over the course of nine facilitated, closed workshops, a diverse group of stakeholders iteratively developed a scientific model to forecast the effects of different management options on outcomes related to oyster abundance, harvest, and environmental performance measures. Using the model, stakeholders considered a variety of oyster management and policy options, including enforcement, rotational harvest, habitat modification and restoration, and combinations of options that included multiple management options in a single model run. Model runs fed into recommendations that were developed for the Maryland Department of Natural Resources (DNR), the agency in charge of Maryland fisheries management.

During OysterFutures, facilitators emphasized that the scientific model was a tool to help stakeholders make decisions and was not the sole guiding force. The model was acting as a boundary object that aided facilitation; it was used to create linkages between environmental science and policy and between different stakeholder sub-group knowledge (White et al. 2008, Lejano and Ingram 2009, White et al. 2010). While boundary objects like scientific models can “foster integrative deliberation” (Lejano and Ingram 2009, p. 653), they are sometimes associated with “mutual misunderstanding”, where different stakeholder sub-groups don’t see the model in the same way (Borowski and Hare 2007 p. 1049). This can result in different attitudes towards models by different stakeholder groups, and therefore different levels of willingness to use the model to inform decision-making.

References

Addison, SJ., & Thorpe, SJ. (2004). Factors involved in the formation of attitudes towards those who are mentally ill. *Soc Psychiatry Psychiatr Epidemiol* 39:228-234.

Andersen, DF., Richardson, GP., & Vennix, JAM. (1997). Group model building: Adding more science to the craft. *System Dynamics Review* 13:187-201.

Barnhardt, R., & Kawagley, AO. (2005). *Indigenous Knowledge Systems and Alaska Native Ways of Knowing.* Anthropology and Education Quarterly 36(1):8-23.

Beach, LR. (1997). *The psychology of decision making: People in organizations*. Thousand Oaks: Sage.

Becker, MH. (1970). Sociometric location and innovativeness: reformulation and extension of the diffusion model. *American Sociological Review* 35:267-282.

Berkes, F. (2009). Indigenous ways of knowing and the study of environmental change. *Journal of the Royal Society of New Zealand*. 39(4):151-156.

Borowski, I., & Hare, M. (2007). Exploring the Gap Between Water Managers and Researchers: Difficulties of Model-Based Tools to Support Practical Water Management. *Water Resources Management* 21(7):1049-1074.

Bottomley, PA., & Doyle, JR. (1996). The formation of attitudes towards brand extensions: Testing and generalising Aaker and Keller’s model. *International Journal of Research in Marketing* 13(4):365-377.

Cash, DW., Clark, WC., Alcock, F., Dickson, NM., Eckley, N., Guston, DH., Jager, J., & Mitchell, RB. (2003). Knowledge systems for sustainable development. *PNAS* 11(14):8086-8091.

Cvitanovic, C., Cunningham, R., Dowd, AM., Howden, SM., & van Putten, EI. (2017). Using Social Network Analysis to Monitor and Assess the Effectiveness of Knowledge Brokers at Connecting Scientists and Decision-Makers: An Australian case study. *Environmental Policy and Governance* 27(3):256-269.

Duncan, R. (2016). Ways of knowing – out-of-sync or incompatible? Framing water quality and farmers’ encounters with science in the regulation of non-point source pollution in the Canterbury region of New Zealand. *Environmental Science & Policy* 55:151-157.

Erickson, B. (1988). The relational basis of attitudes. In *Social structures: A network approach*, ed. B. Wellman and S. D. Berkowitz, 99–121. Cambridge, UK: Cambridge University Press.

Falconi, SM., & Palmer, RN. (2017). An interdisciplinary framework for participatory modeling design and evaluation – What makes models effective participatory decision tools? *Water Resour. Res.* 53:1625-1645.

Festinger, L. (1954). A theory of social comparison processes. *Human Relations* 7:117-140.

Fischer, AP., & Jasny, L. (2017). Capacity to adapt to environmental change: evidence from a network of organizations concerned with increasing wildfire rick. *Ecology and Society* 22(1):23.

Gould, RV., & Fernandez, RM. (1989). Structures of Mediation: A Formal Approach to Brokerage in Transaction Networks. *Sociological Methodology* 19:89-126.

Happer, C., & Philo, G. (2016). New approaches to understanding the role of the news media in the formation of public attitudes and behaviours on climate change. *European Journal of Communication* 31(2):136-151.

Hargadon, AB. (2002). Brokering Knowledge: Linking Learning and Innovation. *Organizational Behavior* 24:41-85.

Henly-Shepard, S., Gray, SA., & Cox, LJ. (2015). The use of participatory modeling to promote social learning and facilitate community disaster planning. *Environmental Science and Policy* 45:109-122.

Lane, D. (1994). Modeling as learning: A consultancy methodology for enhancing learning in management teams. In *Modeling for learning organisations*. Portland, Oregon: Productivity Press.

Layzer, JA. (2008). *National Experiments: Ecosystem-Based Management and the Environment*. MIT Press, Cambridge, MA.

Lejano, RP., & Ingram, H. (2009). Collaborative networks and new ways of knowing. *Environmental Science & Policy* 12:653-662.

Long, JC., Cunningham, FC., & Braithwaite, J. (2013). Bridges, brokers and boundary spanners in collaborative networks: a systematic review. *BMC Health Services Research* 13:158.

Marsden, PV. (1982). “Brokerage Behavior in Restricted Exchange Networks” In: *Social Structure and Network Analysis*. (eds) PV Marsden, N. Lin. p. 201-218. Beverly Hills, CA. Sage Publications.

Miller, TR., Baird, TD., Littlefield, CM., Kofinas, G., Stuart Chapin III, F., & Redman, CL. (2008). Epistemological Pluralism: Reorganizing Interdisciplinary Research. *Ecology and Society* 13(2): 46.

Moser, SC., & Dilling, L. (2010). Communicating climate change: Opportunities and challenges for closing the science-action gap. In: R Norgaard, D Schlosberg & J Dryzek (eds) The Oxford Handbook of Climate Change and Society. p. 161-174. Oxford, UK. Oxford University Press.

Newig, J., & Fritsch, O. (2009). Environmental governance: participatory, multi-level - and effective? *Env. Pol. Gov.* 19:197-214.

Opsahl, T., Agneessens, F., & Skvoretz, J. (2010). Node centrality in weighted networks: Generalizing degree and shortest path. *Social Networks* 32:245-251.

Padula, G. (2008). Enhancing the innovation performance of firms by balancing cohesiveness and bridging ties. *Long Range Plann* 41:395-419.

Pahl-Wostl, C. (2002). Participative and stakeholder-based policy design, evaluation and modeling processes. *Integr Assess* 3(1):3-14.

Paolisso, M., & Dery, N. (2010). A Cultural Model Assessment of Oyster Restoration Alternatives for the Chesapeake Bay. *Human Organization* 69(2):169-179.

Prell, C.., Hubacek, K., & Reed, M. (2009). Stakeholder analysis and social network analysis in natural resources management. *Society & Natural Resources* 22(6):501-518.

Reed, MS. (2008). Stakeholder participation for environmental management: A literature review. *Biological Conservation* 141(10):2417-2431.

Rogers, EM. (2003). *Diffusion of Innovations*, 5th ed. The Free Press, New York, NY.

Rouwette, E., Korzilius, J., Vennix, J., & Jacobs, E. (2002). Group model building effectiveness: a review of assessment studies. *Syst. Dynam. Rev.* 18(1):5-45.

Rouwette, E., Vennix, J., & van Mullekom, T. (2011). Modeling as persuasion: the impact of group model building on attitudes and behavior. *Syst. Dynam. Rev.* 27(1):1-21.

Scholz, G., Dewulf, A., & Pahl-Wostl, C. (2014). An Analytical Framework of Social Learning Facilitated by Participatory Methods. *Syst Pract Action Res* 27:575-591.

Shenk, T., & Franklin, A. (eds). (2001). *Modeling in natural resources management: development, interpretation, and application*. Island Press, Washington, DC.

Stenseth, T., Bråten, I., & Strømsø, HI. (2016). Investigating interest and knowledge as predictors of students’ attitudes towards socio-scientific issues. *Learning and Individual Differences* 47:274-280.

Upham, P., Whitmarsh, L., Poortinga, W., Purdam, K., Darnton, A., McLachlan, C., & Devine-Wright, P. (2009). Public Attitudes to Environmental Change: a selective review of theory and practice. A Research synthesis for the Living with Environmental Change Programme. Research Councils UK. Accessed at: <https://esrc.ukri.org/files/public-engagement/public-dialogues/full-report-public-attitudes-to-environmental-change/>.

Valente, TW., & Fujimoto, K. (2010). Bridging: Locating critical connectors in a network. S*ocial Networks* 32:212-220.

Van der Hulst, RC. (2009). Introduction to Social Network Analysis (SNA) as an investigative tool. *Trends Org Crim* 12:101-121.

Van Voorn, GAK., Verburg, RW., Kunseler, EM., Vader, J., & Janssen, PHM. (2016). A checklist for model credibility, salience, and legitimacy to improve information transfer in environmental policy assessments. *Environmental Modelling & Software* 83:224-236.

Visser, PS., & Mirabile, RR. (2004). Attitudes in the Social Context: The Impact of Social Network Composition on Individual-Level Attitude Strength. *Journal of Personality and Social Psychology* 87(6):779-795.

Voinov, A., & Gaddis, E. (2008). Lessons for successful participatory watershed modeling: A perspective from modeling practitioners. *Ecological Modeling* 216(2):197-207.

Voinov, A., Seppelt, R., Reis, S., Nabel, J., & Shokravi, S. (2014). Values in socio-environmental modelling: Persuasion for action or excuse for inaction. *Environmental Modelling & Software* 53:207-212.

White, D., Corley, EA., & White, MS. (2008). Water Managers’ Perceptions of the Science-Policy Interface in Phoenix, Arizona: Implications for an Emerging Boundary Organization. *Society & Natural Resources* 21:230-243.

White, DD., Wutich, A., Larson, KL., Gober, P., Lant, T., & Senneville, C. (2010). Credibility, salience, and legitimacy of boundary objects: water managers’ assessment of a simulation model in an immersive decision theater. *Science and Public Policy* 37(3):219-232.

Wilson, D. (2009). In S Jentoft, M Bavinck (eds.) *The Paradoxes of Transparency - Science and the Ecosystem Approach to Fisheries Management in Europe*. Amsterdam University Press.

Yuan, YC., & Gay, G. (2006). Homophily of Network Ties and Bonding and Bridging Social Capital in Computer-Mediated Distributed Teams. *Journal of Computer-Mediated Communication* 11:1062-1084.