Chapter 22

Innovations in Collaborative Science: Advancing Citizen Science, Crowdsourcing and Participatory Modeling to Understand and Manage Marine Social–Ecological Systems

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INTRODUCTION

Successful marine conservation in the Anthropocene demands science that better accounts for the interconnected relationships between people and oceans. Fortunately, the last decade has seen a vast increase in the number of interdisciplinary studies, frameworks, and models for explaining complex environmental problems as a function of intertwined social and ecological processes (Liu et al., 2007; Ostrom, 2009; Collins et al., 2011). The popularity of this approach has given rise to a new paradigm in environmental science and natural resource management focused on investigating coupled social–ecological systems (SES), or coupled human–natural systems, noting that many environmental issues cannot be well understood by relying solely on disciplinary scientific approaches alone (Binder et al., 2013). This systems approach has become commonplace in scientific literature and rests upon the notion that human societies are nested within nature and there are complex feedbacks linking humans and their environment (Berkes and Folke, 1998; Liu et al., 2007). Although definitions of SES vary slightly (see for example Redman et al., 2004), they tend to focus on understanding the complexity and dynamic nature of human–environment interactions through a systems-based perspective operationalized either theoretically or empirically.

At the same time that the SES framework has come to prominence and provided new way for thinking about environmental issues in the new era of the
Anthropocene, the last decade has also seen dramatic advances in the tools used by science to understand and manage these coupled systems. Specifically, there has been a considerable increase in the number of studies that include the public or specific stakeholders as a partner in the scientific process through “citizen science” (Cooper et al., 2007; Dickinson et al., 2010; Wechsler, 2014; Shirk et al., 2012; Bonney et al., 2014). Since the inception of citizen science in the mid-1990s whereby Alan Irwin (1995) presented a call to open up science and science-policy processes to the public (Riesch and Potter, 2014), the ideas associated with citizen science have grown to encompass several approaches for including nonscientists and other relevant stakeholders in the creation, deliberation, and communication of scientific research.

Today, the study of citizen science has been so popularized, especially in environmental and conservation research, it has even been suggested that it is its own discipline due to the many impacts that citizen science has had on scientific research and society (Jordan et al., 2015). For example, citizen science has been shown to positively influence research outcomes (e.g., enhanced data coverage, resolution) and outputs (e.g., increasing research publications), environmental decision-making (e.g., action and legislation), and the individuals participating in these programs (e.g., increased personal skills, positive social relationships, and scientific literacy) (Shirk et al., 2012). The “crowd wisdom” generated by the knowledge and observations of citizens has frequently proven valuable for documenting environmental change and supporting or generating new hypotheses for empirical studies (Alessa et al., 2013). However, these outcomes are highly dependent on the degree to which the public is involved in the scientific process, and public inclusion can vary greatly based on the goals and design of the citizen-science project. For instance, a recent NSF-funded report (Bonney et al., 2009) identified three major categories of citizen-science participation, separated by the degree to which the public is included in the scientific process as: (1) contributory projects that are usually scientist-designed and the public is included mainly in data collection; (2) collaborative projects that are structured by scientists but citizens are provided opportunities to provide some input on project design and in data collection; and (3) cocreated projects that are more democratic partnerships where the public is actively engaged with all steps of the scientific process. In addition, Regalado (2015) identified the potential of public-initiated scientific research, in which a project is done by members of the public with professional scientists joining at a later stage. Recognizing that these categories of participation could be even further subdivided (see Shirk et al., 2012), it is reasonable to consider public participation in science as a continuum where both the emergent scientific and social outcomes of citizen-science projects depend on the context of the scientific problem and the structure of volunteer involvement.

Although the literature on citizen science describes it as an increasingly popular way to collaboratively understand ecosystems and collaboratively make decisions about natural resources, to date there is little information that
specifically frames the unique and rapidly evolving challenges and opportunities for citizen science in marine systems. Here, we provide an overview of how citizen science has been applied in marine research and discuss how emerging technologies can be used in the future to improve marine science and conservation. Specifically, we use case studies to demonstrate: (1) how marine applications of citizen science can improve our understanding of social–ecological problems through rapid crowdsourcing of high resolution data; (2) how participatory modeling can capture complex and useful knowledge about the structure and function of marine SES; and (3) the role that web-based technologies may play in crowdsourcing data and harnessing collective intelligence for marine conservation in the Anthropocene (Fig. 22.1).

CROWDSOURCING ENVIRONMENTAL DATA THROUGH CITIZEN SCIENCE: TAPPING INTO THE HUMAN OBSERVING NETWORK

One key outcome routinely associated with citizen science is an improved understanding of our natural world. There is growing evidence that distributed networks of citizen scientists can contribute to scientific understanding of the structure and dynamics of ecosystems, both locally and globally (Bonney et al., 2014). In some instances, citizen-science monitoring has documented changes in ecosystems that would otherwise be prohibitively expensive or logistically impossible to characterize (Wolkovich and Cleland, 2010). Like all research approaches, citizen science has costs, limitations, and vulnerabilities that must be considered. For instance, citizen-science programs that rely on volunteered observations from multiple sources often lack standardized measures of effort. Further, large-scale programs face
significant start-up costs and logistical hurdles. The vast data resources produced by modern web and mobile applications, such as [INaturalist.org](https://www.inaturalist.org) and [ebird.org](https://www.ebird.org), highlight the value of mainstreaming citizen science. However, as with all scientific approaches, innovations in citizen science must coincide with a consistent commitment and evolving efforts to ensure data quality (Crall et al., 2010) (Fig. 22.2).

Theorists in this area have suggested conditions under which such “swarm intelligence” approaches might be feasible, specifically within the context of generating information under “data poor” conditions. For example, crowd-based estimates are thought to be reliable when four conditions are met: (1) the study participants represent diverse opinions; (2) make judgments independent of each other and without outside influences; (3) are free of any fundamental biases that would cause them to systematically over- or underestimate a resource; and (4) truthfully report their estimates (Arlinghaus and Krause, 2013). Under these conditions, researchers can expect that any ill-informed participants are equally likely to overestimate the actual resource size as they are to underestimate it. When estimates are aggregated statistically, their contributions will therefore cancel each other out and the aggregated result will be close to the actual data (Arlinghaus and Krause, 2013). Until recently, tools that provide ways to rapidly design and test experiments to determine contexts under which crowds are

**FIGURE 22.2** Map from Scyphers (2014) showing that the observations of spearfishers provided greater spatial coverage and higher resolution than traditional fisheries monitoring. Each symbol on the map indicates an observation of Indo-Pacific lionfish.
wise (and when they are not), and under what conditions such approaches are appropriate for resource management have largely been limited due to a lack of available technologies. In the context of understanding marine ecosystems, citizen-science observations have proven valuable for documenting ecosystem change, as well as the human dimensions of conservation and management initiatives (e.g., Scyphers et al., 2014; Ward-Paige et al., 2010a). Here, the observations and collective knowledge of fishers and divers have been used to document species declines, shifts in community structure, and inform conservation initiatives (Scholz et al., 2004; Stallings, 2009). For example, the lionfish invasion across the US Atlantic coast is considered the best-documented marine invasion to date and provides an excellent illustration of the value of crowdsourcing environmental data. Over the past decade, lionfish have spread to an area estimated >3 million km², where they often occur in densities far greater than in their native habitats (Schofield, 2010; Schofield et al., 2013). Although the invasion is still relatively new, some early studies have documented alarming reductions in densities of native fish coincided with lionfish invasion (Fig. 22.3).

A recent study by Scyphers et al. (2015) compared traditional fisheries monitoring and three different sources of citizen-science data for detecting the spread of invasive Indo-Pacific lionfish: a federal database of nonindigenous species sightings (i.e., USGS-NAS), a database of fish surveys conducted by trained volunteer divers, and from a targeted survey of recreational spearfishers. They found that citizen observations documented lionfish 1–2 years earlier and more frequently than traditional reef fish monitoring programs. Citizen observations first documented lionfish in 2010, followed by rapid expansion in 2011.
Such studies reveal the value of using fishers as citizen scientists, providing a living observatory network for rapid and broad-scale ecosystem monitoring (Alessa et al., 2013).

Even though such observational approaches to citizen science has been repeatedly demonstrated effective in marine ecosystems, there are some additional challenges that must be considered. From a scientific perspective, underwater visual surveys may overestimate the abundance of large and highly mobile species if the potential for species entering and exiting the study area is not accounted for (Ward-Paige et al., 2010b). From a cost and logistics perspective, citizen science in marine ecosystems require specialized gear and skillsets (e.g., snorkeling, SCUBA) that are often costly and result in a narrower pool of potential participants. As with any research design that involves complex environmental data collected by citizens or stakeholders, the nature of the community involved and how the data are collected and reported must be considered in the design of marine citizen-science projects.

In addition to increasing the scale and scope of biological observations, citizen science can also be used to rapidly assess how well conservation and management initiatives are performing. In fisheries, management often relies on the compliance and participation of fishers for effective policies. For instance, fish captured from deep water sometimes experience internal injuries caused by barotrauma (i.e., gas expansion in swim bladder, body cavity). A management policy aimed at increasing post-release survival of discarded fish relies on the mandatory use of venting tools (i.e., hollow syringe-like devices) to release expanded gases and mitigate the effects of capture. However, the effectiveness of venting is disputed resulting in a management issue surrounded by uncertainty. A recent study by Scyphers (2014) sought to better understand the human dimensions and efficacy of this participatory management strategy. Using an online survey, anglers revealed that there is high “buy-in” among recreational fishers and considerable belief that venting is beneficial for released reef fishes. However, their work also showed that a substantial proportion of anglers, including some highly experience anglers, are not implementing the management measure effectively (Fig. 22.4). For instance, when asked to identify the ideal location for inserting the venting tool, many anglers indicated the protrusion of the fish’s stomach or any adjacent major internal organ. Considering that a large proportion of anglers implementing venting techniques may be doing so improperly, the authors concluded that more attention should be directed toward angler considerations, behaviors, and the social costs of mandates to avoid losing the trust of anglers.

PARTICIPATORY MODELING TO UNDERSTAND SOCIAL–ECOLOGICAL COUPLING

In addition to crowdsourcing environmental data, citizen science has also been linked to participatory approaches that seek to answer broader questions about the complex structure and function of marine SES (Nayaki et al., 2014; Gray et al., 2017a). Given the wide range of stakeholders that use and interact with
In marine environments, knowledge about how ecosystems and social systems interact is diverse (Stier et al., 2017). In fact, it had been suggested that in order to create more sustainable management strategies, stakeholders must forge new relationships to enhance multidirectional information flows, learn from each other, and together, develop flexible ways of understanding and managing their environments (Carpenter and Gunderson, 2001). Although there is general agreement on the importance of citizen involvement within adaptive decision-making processes, it is unclear how best this should happen, what form it should take (Abelson et al., 2003; Rowe and Frewer, 2000), and how participation in environmental knowledge generation contributes to shared understanding of environmental issues. What constitutes “appropriate” venues of knowledge sharing varies within and between stakeholder groups, research design, and decision-contexts, and is highly influenced by social conditions in which decisions are made. These conditions include hierarchies like differences in values, power struggles, degree of participation of those affected, and the inherent uncertainty of complex system behavior (Biggs et al., 2011).

As a result of these issues, participatory approaches and software tools have emerged over the last decade as a way to model and collaboratively discuss the structure and function of SES with stakeholders. The justification for including stakeholders in scientific modeling practices is based on the acknowledgment that: (1) model-based reasoning is a predominant and preferred basis of environmental decision-making in contemporary environmental management; (2) public participation is an essential component to informed environmental decision-making; and (3) stakeholder groups often hold unique and complex knowledge that is useful for understanding the dynamics of SES (Gray et al., 2015).
This increased interest in participatory modeling has given rise to a range of stakeholder-centered modeling tools, practices, and guidelines that aim to provide decision support in participatory environmental planning contexts (Voinov and Bousquet, 2010; Voinov et al., 2016). However, even with this increase in tool and software development, some critics have cautioned that diversity of modeling practices does not necessarily indicate diversity in function (Jones et al., 2009) and the most significant contribution of including stakeholders in modeling is community learning, facilitated by structured knowledge sharing between citizens, scientist, and managers (Voinov and Bousquet, 2010).

Given the popularity of participatory modeling approaches in the last few years, synthesis research has begun to identify trends in both the process and products associated with participatory modeling (Gray et al., 2017b) and their implications for improved marine conservation decision-making. For example, Sandker et al. (2010) found that although there are several common tools associated with the practice of participatory modeling, including Bayesian methods, Agent-Based Modeling, and Systems Dynamic Modeling among others, the largest contribution of engaging stakeholders in modeling included stimulating cross-sector planning and facilitating discussions that helped participants to confront the drivers of environmental change and to recognize trade-offs in management strategies. The authors also found evidence of environmental decision-making outcomes, such as the coproduction of knowledge leading to management decisions as a result of the modeling process, but this was largely dependent on types of stakeholders that were included in the process. In terms of the modeling processes, case studies evaluated in their review varied in terms of the degree of participation among stakeholders, measured in terms of the amount of time that scientists, non-governmental organizations, and stakeholders collaborated, which ranged from creating models in a single workshop to prolonged involvement with a group of stakeholders over several months (Sandker et al., 2010). Others have also suggested that different modeling techniques may be more or less appropriate to employ given variation in the community engaged in the modeling process and the types of modeling practices that are useful for a given decision-making context (Gray et al., 2015).

In terms of using participatory modeling methods for marine conservation, there has recently been a considerable increase in the number of case studies that adopt these approaches. These marine resource-based participatory modeling applications include marine spatial planning (Gray et al., 2014) and coastal hazard adaptation (Henly-Shepard et al., 2015). However, given the mandates for stakeholder involvement in policy making in the EU and in the USA (Magnuson Stevens), participatory modeling seems to be particularly useful for fisheries management to understand marine systems that span multiple ecological scales using several different system-based modeling software packages.
For example, at the local scale, Webler et al. (2016) used a dialog-based group concept mapping called VCAPS (vulnerability, consequences, and adaptation planning scenarios) and System Dynamics Modeling to elicit and integrate both local and expert knowledge about vulnerability to climate change in a lobster fishery in Maine. The study involved a prolonged engagement period with ecologists, lobstermen, and other community members over a 2-year period, which included two concept mapping workshops to understand the structure of social–ecological dynamics of the fishery related to climate change impacts, and three system dynamics workshops to build a functional and parameterized model to predict how fishing effort and climate change relate to economic productivity in the fishery.

On a more regional scale, Gray et al. (2012) used fuzzy cognitive mapping with different stakeholder groups involved in the summer flounder fishery in the mid-Atlantic coast in the USA. The authors conducted a series of interviews with 35 individuals from 6 different fishery stakeholder groups, including recreational fishermen, commercial fishermen, members of the pre- and postharvest sectors, environmental NGO representatives, fisheries scientists, and fishery managers that were selected based on their involvement in the policy-making process. The goal of this study was to understand how local expertise reflects different beliefs and values, and how these more pluralistic views of marine dynamics could be integrated and used to decrease uncertainty surrounding the dynamics of the fishery. The result was a wider scenario-capable systems-based model that integrated the knowledge of all stakeholder experts involved in the fishery, thus providing a more complete view of the systems being managed (Fig. 22.5).
FUTURE DIRECTIONS OF USING CITIZEN SCIENCE TO UNDERSTAND MARINE SES

Citizen science has already proven to be very effective in expanding data collection capacity, enhancing our understanding of how human and natural ecosystems are coupled, and in improving stakeholder participation in decision-making about these systems. However, new frontiers and tools are increasingly emerging that hold considerable promise for more collaborative forms of marine science in the future. Although many of these new approaches, and specifically software tools, were not developed for use in collaborative science or with natural resource management in mind, new web-enabled platforms that capture the “wisdom of the crowds” or types of “collective intelligence” now provide marine scientists with new and powerful approaches to better understand and manage marine systems. We identify two of these emerging web-based approaches (e.g., UNU and Mental Modeler) to collaborative research and modeling, and discuss some of the trade-offs and considerations associated with the selection of different approaches.

Innovations in Web-Based Collective Intelligence

While still in the early stages of development, new web-based applications such as UNU (www.unu.ai) (Rosenberg, 2015) provide exciting and novel approaches to harnessing collective intelligence of marine stakeholders. Such “swarm intelligence” platforms hold great promise for (1) identifying value-based judgments regarding the types of scientific research that should be conducted; and (2) providing new ways to estimate and forecast resource assessments by engaging groups of knowledgeable stakeholders that interact with marine systems to share their knowledge and opinions. The design of the UNU interface is modeled after “biological swarms,” enabling groups of online users to individually pose questions (selected by a moderator) and, as a group, answer these questions, make decisions, and resolve dilemmas by working together in unified online dynamic system (Rosenberg, 2015). The platform is synchronous, meaning users can explore decision spaces together, and the software structures these online social groups of users through a process of “social swarming” in real time intended to promote group convergence on a preferred solution in a matter of seconds. Fig. 22.6A and B show current testing of the software with online user groups, where a question is posed about whether more resources should be devoted to the colonization of space. The crowd collectively settled into the answer of “Yes” provided with alternative options “No,” “Maybe,” or “Bad Question.” To arrive at the answer, all logged-in users use individual horseshoe shaped magnets to pull a circle toward one of several predefined answers (which can themselves be generated by the group).

While not currently used by natural resource users, Fig. 22.6C and D show hypothetical conditions of software use with groups of scientists, commercial fishermen, recreational fishermen or combinations of these, or other knowledgeable
groups to: (1) estimate current biomass of economically important fish stocks; and (2) estimate social changes such as the percentage of fishermen that have left the fishery since 2005. Tools like UNU may provide clear mechanisms to test often hypothesized, but empirically untested ideas using “wisdom of the crowd.” For instance, such approaches could have the potential to generate independent estimates of population sizes for natural resources (e.g. stock estimates) which can be aggregated to approximate true sizes (Arlinghaus and Krause, 2013). While previous researchers have suggested averaging individual resource estimates collected through surveys as one of the most straightforward ways to collect such crowdsourced data (Arlinghaus and Krause, 2013), relatively few studies have
attempted to compare averaged resource estimates to scientifically or empirically developed resource assessments, with some recent exceptions (see Predavec et al., 2016). It has been noted that wisdom of the crowd, collective cognition, and swarm intelligence all essentially refer to a process of individuals independently acquiring information and processing this information through social interaction to produce a solution to a cognitive problem that cannot be arrived at by any single individual (Krause et al., 2010).

Other new web-based technologies that take a unique approach to collaborative science include Mental Modeler (www.mentalmodeler.org) and DESIM (descriptive executable simulation modeling), platforms which provide scientists new ways of “crowdsourcing” mental models of groups of natural resource stakeholders asynchronously. Mental Modeler, developed by Gray et al. (2013) is an online fuzzy cognitive mapping (FCM) software allowing users to individually or collaboratively create dynamic representations of their belief systems, or mental models, about the dynamics of natural resource and other complex systems. DESIM, developed by Pfaff et al. (2016) is a complementary, but independent, software package that decomposes the FCM generated in Mental Modeler into pairwise comparisons (Fig. 22.7) which can then be converted into online survey questions and administered to large groups of users online to validate model structure and evaluate the degree to which complex understanding of resource systems are shared across local and scientific experts. Using interviews or web-based approaches to develop FCMs, DESIM asks the online participants to agree/disagree with causal connections in the model and to compare pairs of existing connections with regard to their strength. Analytical hierarchy process (AHP) is used to compute the strength of connections, based on all pairwise comparisons by all online study participants, thus providing a very robust, “crowdsourced” FCM model. Such approaches allow the complex structure of SES to be defined along with the areas of uncertainty of the dynamics of SES. Additionally, because FCMs are based on graph theory and matrix algebra, these platforms can be used to generate environmental and social change scenarios based on crowd knowledge to understand how these complex systems may react to future or hypothetical changes or perturbations.

Fig. 22.7 shows a hypothetical FCM collected through interviews with several coastal experts about the relationship between oil and gas operations, unexpected oil spills and their structural relation and influence on ecosystem, and economic dynamics of a coastal area. Once individual or group mental models are generated with Mental Modeler through interviews of focus groups, DESIM allows pairwise relationships to be converted into individual survey questions, which can be administered to large groups of stakeholders online to validate or evaluate the degree to which mental models about marine SES are shared across marine stakeholder groups. Further, the final crowdsourced model reconstructed through survey responses can be subjected to scenario analysis and used to estimate how qualitative changes in system states are linked with social or ecological conditions under different policy, social, or natural conditions.
FIGURE 22.7  FCM created in Mental Modeler can be translated into a series of survey questions in DESIM which can be translated back into a “crowdsourced” mental model to estimate structure and dynamics of marine systems.
Trade-Offs in Participatory Modeling Approaches: Selecting the Right Tool for the Job

As more participatory approaches to collaborative modeling continue to become more mainstream with technological advances (Voinov et al., 2016), it is important to select participatory modeling methods based on the community involved in the modeling process, research questions, or management goals, and how each tool differs across dimensions (Gray et al., 2017b). Although the theory behind each of these software-based or web-enabled tools continues to develop with new methodological and technological advances, the strengths and weaknesses of different approaches should be taken into consideration when designing collaborative science projects.

Certain participatory modeling methods may be more or less amenable to different types of marine stakeholders involved in the modeling process based on the amount of training required to create and analyze a model or to provide data points for an assessment. Although narrative scenario analysis and qualitative concept mapping lend themselves to use across a wider range of communities because they are more flexible than semiquantitative approaches, the output of these models is often not dynamic, thus limiting their ability to be used to evaluate competing system states through post hoc analyses (Gray et al., 2015, 2017b). Additionally, although to varying degrees most methods allow stakeholders and scientists to define the concepts, components, or variables that constitute the state space of the system modeled, some methods are more flexible in terms of the types of relationships that can be defined between variables. FCM and Agent-Based Modeling, for example, can represent feedback relationships between variables, whereas Bayesian belief network relationships are unidirectional. Although to some extent, all SES modeled through these efforts are defined in terms of time and space, the degree to which model outputs can be interpreted in spatial or temporal units by stakeholders varies and thus may influence analytical abilities to draw meaningful conclusions that facilitate management action. When considered together on a spectrum, as tools transition from more flexible and qualitative to more parameterized and semiquantitative, ease of stakeholder use decreases while the ability to explicitly evaluate competing system states increases. Further, although semiquantitative approaches may provide a wide range of opportunities for post hoc analysis, they may limit the degree to which stakeholder values and knowledge are integrated into model-based assessments.

CONCLUSION

Although innovations in citizen science have tested new ways for researchers, managers, and society to collaboratively understand and collaboratively make decisions about ecosystems natural resources, how citizen and other participatory forms of science will support marine conservation in the future is unclear. However, given new innovations and a strong history of success, marine
scientists will likely have access to a diverse toolkit allowing them to harness citizens’ knowledge and participation in new ways in order to: (1) prioritize the scientific questions that are asked about marine systems through web-based technologies (Rosenberg, 2015); (2) understand the complex nature and dynamics of these systems based on integrating a range of local expert knowledge (Gray et al., 2012); (3) use stakeholders to collect empirical data about changes in these systems (Scyphers et al., 2015); and (4) adaptively evaluate whether management decisions having desired impacts to be considered as new research questions are developed (Scyphers et al., 2013). Such collaborative science approaches are promising and will only continue to expand, transitioning the nature of knowledge by diverse stakeholders away from being a management liability that impedes conservation action (Biggs et al., 2011) into strength. Citizens, scientists, and managers collectively seek to define, understand, and address modern marine problems presented by the complex and dynamic nature of the marine environment. For both science and conservation, collaboration and inclusive participation will be critical for understanding and responding to the novel and rapid changes anticipated to occur in the Anthropocene.

REFERENCES


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