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Modeling with citizen scientists: Using community-based modeling tools to develop citizen science projects

Steven Gray[a], David Mellor[b], Rebecca Jordan[c], Alycia Crall[b], Greg Newman[d]

[a] *University of Massachusetts, School for the Environment, 100 Morrissey Blvd, Boston, MA 02170. Email: stevenallangray@gmail.com*
[b] *Virginia Polytechnic Institute and State University, Department of Forest Resources and Environmental Conservation, 310 West Campus Drive Blacksburg, VA 24061. Email. mellor@vt.edu and Email: crall@vt.edu*
[c] *Rutgers University, Department of Ecology, Evolution and Natural Resources, 14 College Farm Road, New Brunswick, NJ 0890. Email: rcjordan@rutgers.edu*
[d] Natural Resource Ecology Laboratory, *Colorado State University. Fort Collins, CO 80523.Email: Gregory.Newman@colostate.edu*

Abstract: Although model-based reasoning is often at the center of environmental science and management, the process of constructing, refining and empirically validating scientific models is not often made explicit to participants in many citizen science programs. The lack of attention that modeling receives in citizen science programs is likely attributable to resource constraints, given that scientific modeling often requires considerable training and scientific software tools are not easily accessible to members of the general public. To address these constraints, we describe the development and use of a fuzzy-logic cognitive mapping software called Mental Modeler (http://www.mentalmodeler.org/), embedded within a citizen science web portal (www.citsci.org) and curriculum that allows scientists, environmental managers, and citizen scientists to: (1) collaboratively define environmental issues of shared concern, (2) model and represent assumptions, evidence, and existing information about these issues, (3) run scenarios to discuss potential research or management options, and ultimately (4) co-develop citizen science research and environmental management plans with science professionals. Our program uses an adaptive management framework to facilitate discussion between project managers and volunteers on: the current and desired state of the natural resource system being managed; their plan for a management action; project implementation; and evaluation and communication of results. Using data collected from one community group who worked with professional scientists and land managers on a local project in Virginia as a case study, we outline the architecture of the modeling software, describe participant interaction with the modeling tool and website, and review the project generated.

Keywords: participatory modelling; citizen science; fuzzy-logic cognitive mapping; public participation in scientific research.

1 BACKGROUND

Including the public in environmental monitoring, research and decision-making has been an area of growing research among environmental researchers that spans the natural and social sciences (Reed 2008). The interest in this area has given rise to several paradigms related to public participation in environmental decision-making including citizen science and participatory modeling. Although these areas of research share similar goals and provide a space for integrating the general public and specific stakeholders into environmental management, they each have strengths that can be merged. Citizen science offers the opportunity to engage in authentic environmental research while participatory modeling engages individuals in community level environmental management. Here we contend that individuals can have a greater role in environmental decision-making if afforded the opportunity to directly collect information and data to inform resource management models. Below, we describe citizen science and participatory modeling and share our design for a model-based citizen science and participatory management program.

To begin, the term ‘citizen science’ falls under the umbrella of public participation in scientific research (PPSR, see Bonney et al. 2009) and has been shown to result in different outcomes, based on the structure of the project, including contributions to (1) scientific research (e.g. increasing research findings and publications); (2) environmental decision-making (e.g. action, legislation, and positive social relationships); and (3) the individuals participating in these programs through increased personal skills and knowledge (Shirk et al. 2012). Although the term citizen science generally refers to public contribution to scientific research, the type and degree of participation across different citizen science programs vary. A recent NSF-funded report (Bonney et al., 2009) defined three major categories of projects including: (1) contributory projects that are usually scientist designed where the public is included mainly in data collection; (2) collaborative projects that are projects that are structured by scientists but citizens are provided opportunities to provide some input on project design and in data collection; and (3) co-created projects which are more democratic partnerships where the public is actively engaged with all steps of the scientific process. Not surprisingly, the majority of citizen science projects fall into the first category where the volunteers are used mainly to increase data collection capacity. Although some notable examples of co-created projects do exist (see Nicosia et al. 2014), the last decade of research on citizen science programs indicate that currently scientists, practitioners, and participants lack the tools and frameworks required to enable the public and scientists to ask and answer questions of mutual interest or concern (Gray et al. 2012).

During the same time that citizen science has come to prominence, participatory modeling has also been a growing area of research. The justification for including stakeholders in participatory modeling is based on the acknowledgement 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 social-ecological systems. This increased academic and applied interest in participatory modelling has given rise to a range of stakeholder-centered modeling tools, practices, and guidelines that aim to provide decision support in participatory planning contexts (Gray et al. 2013). 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. 2008) and that the most significant contribution of including stakeholders in modelling is community learning, facilitated by structured knowledge sharing (Voinov and Bousquet 2010).

Although both citizen science and participatory modeling have provided useful frameworks, methods, and tools for engaging the public with environmental research, monitoring, and decision-making; software tools and programmatic guidelines that couple these approaches are unavailable. Additionally, while many researchers have indicated that citizen science holds considerable promise for increasing the quality of environmental decisions and social-ecological resilience (Shirk et al. 2012), empirical reviews of citizen science programs indicate that citizen participation in the scientific process is largely limited to data collection (Bonney et al. 2009) and that the majority of these projects do not contribute directly to management decision-making (Conrad and Hickey 2011).

To address these issues, we present the architecture of a citizen science program with a web-based curriculum, an embedded fuzzy-logic cognitive mapping modeling software, called Mental Modeller (www.mentalmodeler.org), and a web-based interface for data collection (www.citsci.org) to draw on the strengths of both of these fields to increase stakeholder contribution to environmental science and management. Specifically, our program seeks to increase the degree of participation from citizen groups as well as the representation of local stakeholder knowledge to increase the quality of environmental decision-making by allowing scientists, environmental managers and citizen scientists to: (1) collaboratively define environmental issues of shared concern, (2) model and represent assumptions, evidence, and existing information about these issues, (3) run scenarios to discuss potential research or management options, and ultimately (4) co-develop citizen science research and environmental management plans with science professionals.

2 PROGRAM, SOFTWARE DESIGN AND WEB-TOOL DESIGN

We present the architecture of a citizen science program with an embedded modeling software and web-based tool designed to draw on the strengths of both of these fields to increase stakeholder contribution to environmental management. Our tools include (1) ecological and adaptive management training curriculum; (2) a fuzzy-logic cognitive mapping software which allows citizen groups to define a problem context that represent their knowledge, and run scenarios and (3) a web-based portal which allows citizen groups to validate their model empirically through data collection and analysis. We begin by providing an overview of these three components and then demonstrate the deployment of the tools working with one citizen group in Virginia in our collaborative space to develop an environmental management project co-developed by a volunteer group working with professional land managers, that addresses an environmental issue of local concern.

2.1 Collaborative Conservation Training

The first component of our program is a unified training module that includes both content area and practice-oriented instruction given through an online, asynchronous learning environment embedded with modelling and collaborative learning tools. The goal of the online learning environment is to prepare participants to engage in collaborative or co-created citizen science projects (see Bonney, et. al. 2009, for an overview of PPSR project models). We chose to focus on engagement in co-created and collaborative citizen science projects because of the potential for science and environmental learning that such projects offer and because they may create opportunities to increase the degree of volunteer participation in multiple steps of the scientific process. Because of the increased commitment required of such projects, we chose to focus on a population that was motivated to participate in this type project who were also sufficiently willing and interested in increasing their level of participation in local environmental management.

The focus population for the online learning tool is the Virginia Master Naturalists, a group of volunteers tasked with assisting in citizen science, stewardship, and education in Virginia's natural resources. Like other states' Master Naturalist programs, participants are required to undergo an initial basic training program (40 hours of classroom and field work) and conduct volunteer work and advanced training every year for recertification. Also similar to other master naturalist programs, participants in the Virginia program tend to be older, more educated, and wealthier than the general population (unpublished data). Many are retired with at least some previous experience with natural resource conservation.

2.1.1 Collaborative Conservation Training: Content Area Instruction

The curricular content design includes an online, asynchronous program focused on providing information on ecology, conservation, the use of models in scientific reasoning, basic statistics, the use of the Mental Modeler software tool (described in detail, section 2.2), and an overview of the process of adaptive land management. This content is given in a series of 13 narrated videos (from 8-25 minutes each), each accompanied by hand-outs to download, an outline, and a short quiz that has three to five multiple choice questions for instant feedback, and three to five short answer questions designed to engage participants in the material. Aside from using these questions as self-assessment to participants they are also used as data to track individual and group-level learning. The training page also contains a discussion forum for interaction between students and a project coordinator.

The ecology content focuses on energy and food webs, nutrient cycles, population dynamics, interactions, community structure, and ecosystem services. These areas were chosen in order to give a relatively broad overview of concepts sufficient to further self-directed learning. The adaptive management content, on the other hand, was selected to focus the group into developing a conservation strategy based on the needs and interests of its members. It covers discussing the current and desired states of an ecosystem, creating a management plan for conservation, plan implementation, evaluation, and sharing management plan results. Each lesson in the adaptive management section consists of resources that may be useful to the group in that stage in the curriculum, for example, the project evaluation stage has several habitat evaluation tools to measure the effects of a possible environmental intervention.

2.1.2 Collaborative Conservation Training: Practice-Oriented Instruction

The practice-oriented instruction focuses on using the software, Mental Modeler (section 2.2) and web-based tools CitSci.org (section 2.3) in the development of an adaptive management plan. Each stage of the adaptive management plan (discuss, plan, implement, evaluate, and share) is given a single page and consists of individual discussion forums with question prompts appropriate to the stage and a collaborative "wiki" space to enter the group consensus for each stage. In addition, the "discuss" page has space for individuals to create, upload, and discuss their individual or group models, and the "implement" tab has the CitSci.org project information page embedded. The CitSci.org project information page, described in more detail below, enables individuals to create project data sheets, upload observations, view data, and share resources appropriate to the task (e.g. identification guides, tutorials, maps, etc.). Finally, the "share" page compiles the plans entered into each wiki and provides a structure for sharing the results of the project with relevant stakeholders and informing the next round of conservation management based on previous findings. Throughout the curriculum, participants also have access to contact information for scientific and management experts in their local area who can provide feedback as the group structures the environmental problem, defines the questions to be addressed and creates a related project that deals with these issues.

2.2 Mental Modeler Software

Embedded as part of the training is a cognitive mapping software called Mental Modeler. The software was designed to enable citizen scientists and environmental professionals to: (1) construct a qualitative conceptual model of a problem context; (2) provide evidence of these hypothesized or known relationships defined within the model; (3) define the unit of measurement to support the relationships defined; (4) develop scenarios and evaluate system change under plausible management or environmental change conditions; and (5) revise their model based on the model output and use this information to developed detailed data collection and analysis plans. The architecture of the program is designed to allow stakeholders a flexible way to transition their disparate, loosely-connected and largely qualitative knowledge about an environmental issue into a tractable format which can be validated through the generation of empirical evidence (Gray et al. 2013).

Mental Modeler is based on Fuzzy-logic Cognitive Mapping (FCM) (see Kosko 1986 and Ozesmi and Ozesmi 2004) and comprised of three main user interfaces: (a) the concept mapping interface that provides a space for model building and parameterizes model construction in the format required for FCM analysis; (b) the matrix interface that allows the structural properties of the cognitive map to become clear by examining pairwise relationships; and (c) the scenario interface which allows stakeholders to run and compare change within the system under different potential scenarios and revisit and revise their models in the concept mapping interface in light of this new information.

2.2.1 Concept Mapping Interface

The concept mapping interface allows stakeholders to structure the dynamics of an environmental problem using a conceptual space by defining components (i.e., variables or nodes) that comprise natural resource systems and defining the relationships between these components. By first adding components (using a plus sign and then labelling each component that is added), individuals or groups can begin model development by brainstorming all of the important components hypothesized that are related to understanding the system or problem that is being addressed.

After components have been defined, the relationships between components can be added by using directional arrows which indicate the amount of influence one component can have on another, called edge relationships. Components included in the model can have positive (high (+++), medium (++), or low (+)), negative (high (---), medium (--), or low (-)) or no (no relationship defined) edge relationships. The software is developed to parameterize these qualitative relationships in the manner that is required for FCM-based scenario analyses and represented in the software using directed arrows of different colors (red arrows for negative and blue arrows for positive) and line thickness for degree of influence (the thicker the line the more influence). As citizen science groups individually or collaboratively define qualitative weights of edge relationships between components the software translates these qualitative values (i.e. "fuzzy" approximation of influence) into the quantitative values between -1 (high negative) to 1 (high positive) used in the matrix interface.

The concept mapping interface also includes additional functionality enabling the concept map to be layered with additional information based on the knowledge of the stakeholders creating the model. Specifically, as the concept map is developed (nodes, edges and edge weights), participants can also define web links or qualitative descriptions of the evidence used, which lead to the representation of a node or edge, the degree of confidence about the existence of the relationship (on a 5 point Likert scale from Not Confident to Very Confident) as well as define the unit of measurement that might be used to collect data to validate perceived relationships between components. These features are intended to encourage users to support their claims with evidence, define the degree of uncertainty within their claims, and ultimately used to enable users to translate their models into data collection plans (Figure 1).

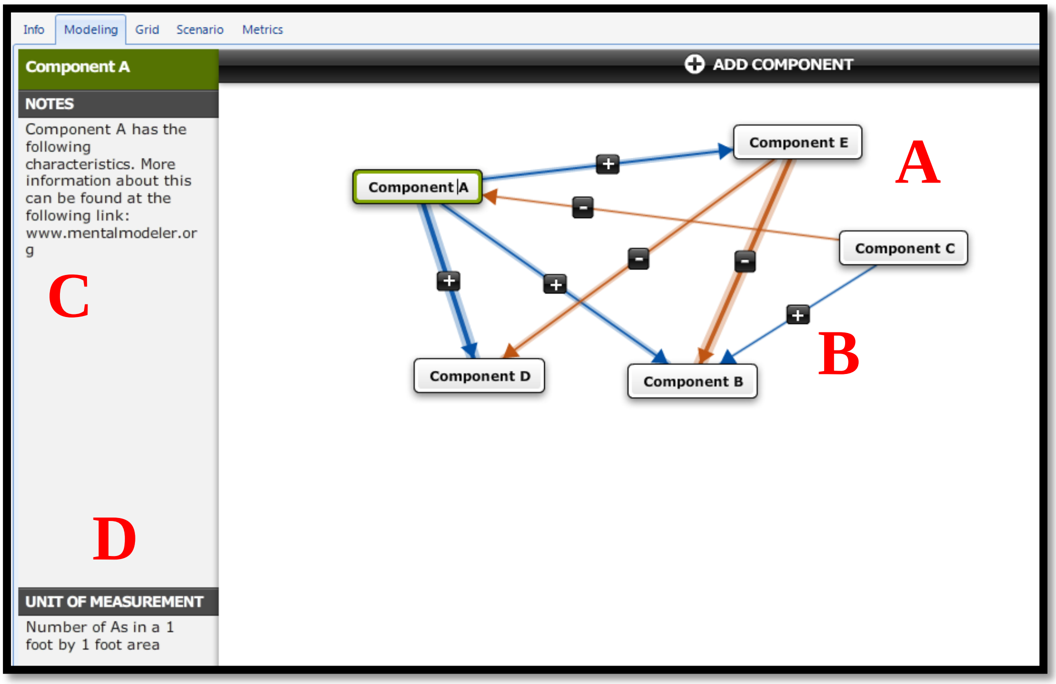

Figure 1. Screenshot of Mental Modeler software Concept Mapping interface that includes (A) defined components (B) directional edge relationships and weights defined between components (C) notes about components and relationships to be included as evidence for inclusion in the model and (D) proposed unit of measurements for components.

2.2.2 Matrix Interface

Mental Modeler also includes a Matrix interface that converts the concept map built in the Concept Mapping interface into a structural matrix. The matrix interface lists all components included in the model on the *i* and *j* axes and translates the amount and direction of relationships. This interface is simply a different representation of the conceptual model, placing the concept map in the form required for the matrix algebra calculation used for the Scenario interface (see Kosko 1986). The Matrix interface can easily be revised based on the original concept map once the users familiarize themselves with the structure of the tool and changes made the matrix interface will change in the concept-mapping interface and vice versa.

2.2.3 Scenario Interface

The third interface in our software is the Scenario interface where artificial scenarios can be run and compared. The scenario interface indicates the amount of relative change in the components included in the model based on the edge relationships defined in the Concept Mapping interface for the chosen scenario. Users can decide what scenario to run based on probable, improbable, gradual and extreme changes to the system. To run a scenario, each variable can be set at a value between qualitatively defined states of +++ (strong negative change) and --- (strong positive change). Relative change in the system is displayed as a bar graph to indicate how components might react under a given scenario which is viewed compressively as a system state change.

2.3 CitSci.org

Finally, after citizens are trained and citizen scientist and professionals have a working representation of their hypothesized relationships between independent and dependent variables, empirical validation and/or rejection of their system model can be conducted through field data collection using the embedded CitSci.org data management and visualization platform (Newman et al. 2010). The CitSci.org cyber-infrastructure is a web application where citizen scientist project managers can approve members and structure citizen science community who, in turn, can collect and submit environmental monitoring data to validate claims in their models. Data can be submitted through use of customizable datasheets created by project managers to suit her/his project needs. Datasheets can be constructed to measure any organism and associated attributes or site characteristics by selecting from existing measurements (e.g., stream pH, height, length, sex, weight, cloud cover etc.) or creating their own (number of spots on leaf, etc.). Because CitSci.org is a shared common open data repository and management site for citizen science projects globally, efforts are made to standardize measurements and protocols used across projects. Data are then submitted by approved project members using the datasheets created by project managers and then represented as both tables and maps for everyone to explore. Additional features include an easy invite members tool, pre-defined monitoring locations support, bulk upload for managers of legacy data, and real-time dynamic charts for trend visualization.

3 CASE STUDY EXAMPLE:

To demonstrate the use of our tools together, we present data collected from one chapter of the Virginia Master Naturalists, working with professional land managers in Virginia, to (1) define a research question of local interest related to an invasive species and ecosystem integrity, (2) develop a model of the ecosystem based on their understanding of the problem, and (3) implement a conservation project by structuring data collection in citsci.org to better understand the dynamics of the issue and define possible management actions. Based on local interest in, and value of, a Nature Conservancy-owned property that contained a rare, fire-mediated pine savannah habitat and the endangered Red cockaded woodpecker, members of the local Master Naturalist chapter chose this concern. They met with a local land manager to ask questions about current threats to ecosystem health and stability in the region. The land manager, who was an employee of the state, identified a growing concern over the establishment of Japanese stilt grass (*Microstegium vimineum)*, which had just recently been identified in the area. It is feared that the fire-managed land may be especially sensitive to this invasive grass because of its increased germination post fire and because of the increased intensity of fires because the species was associated with higher fuel loads (Fryer, 2011).

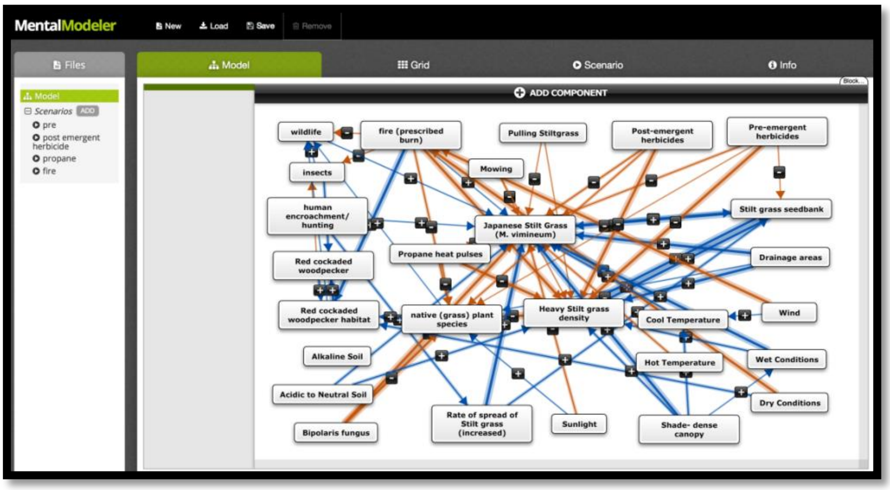

Figure 2. Screenshot of Mental Modeler software Concept Mapping interface that shows refined model of stilt grass issue collected from participants

While participants continued to work through the curriculum and after meeting with the land managers, group members began modeling their understanding of the issue in terms of ecological dynamics related to fire and different management techniques. After volunteers developed individual models, the models were merged and reviewed by the group (Figure 2). The merged model (sometimes called the 'community model' (Ozesmi and Ozesmi 2004)) was refined through collaborative discussion. The community model was then used to define areas within the model where there was agreement, components and relationships about which the participants were confident, and identified uncertain areas in the model. After participants were content with their model, potential system states ('futures') with no management and with competing potential management options were then developed (Figure 3). These scenarios and the discussions that followed identified areas (components and relationships) that could be validated through empirical measurement via data collection.

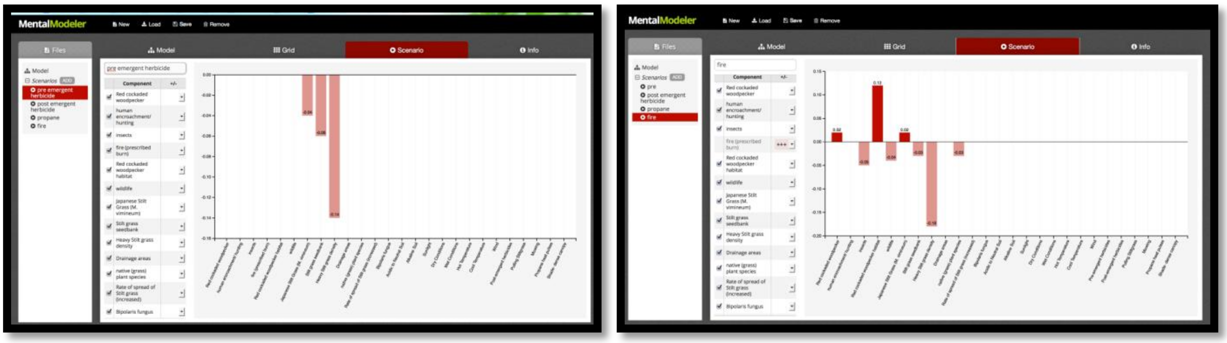

Figure 3. Screenshot of Mental Modeler software Scenario interface that includes ecosystem state under business as usual (left) and with a management option in place (right).

After conducting their literature review and receiving feedback from a scientist and stilt grass expert, participants revised their models and have developed an experimental design to measure the cost effectiveness of various treatment regimes. Based on this information, participants chose to use a randomized block design to measure the effect of four different treatments (three experimental and one control) among 48 plots among five sites within the land areas being managed. The treatments include different combinations of a post-emergent herbicide and propane heat pulses to repeatedly treat each site.

4 DISCUSSION

In this paper, we discussed a citizen science program that engaged participants in modeling to help meet natural resource goals. Our approach involved using software designed for participants as well integrating educative, collaborative, and self-paced learning tools. Using this approach, required resources in terms of time and money were expended upfront and prior to participant engagement. This allowed for ready-made and user-friendly tools, which helped us to reduce frustration with the online learning environment. Although their data collection is still on-going, we measured a significant increase in participants' confidence in the potential effectiveness of their conservation plan (Mann Whitney U Test, $U = 58$, $p = 0.047$) pre and post the learning and planning process. Further all participants reported that they would engage in a project like this again.

5 CONCLUSIONS AND RECOMMENDATIONS

In this project, we demonstrated that merging participatory modeling and citizen science could provide improvements to management goals, while maintaining participant satisfaction and engagement in science. For others seeking to do so, we stress that the process of modeling needs to be central to the projects in which participants are engaged. This is to avoid participant ambivalence about modeling which, can feel at times, esoteric. In addition, others must have the necessary resources established prior to participant engagement, and allow for on-going support, especially early in the project planning process. While we are still early in the process of working with participants, we have enough evidence to suggest that citizen science and participatory modeling are not only similar in goals, but can be similar in practice.

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