Title: Combining participatory modelling and citizen science to support volunteer conservation action

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1 **Abstract:**

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3 The popularity of both citizen science and participatory modelling has given way to a growing
4 number of case studies that all outline the benefits of more inclusive forms of conservation
5 planning. Citizen science offers volunteers the opportunity to engage in environmental research
6 while participatory modelling engages individuals in community-level environmental decision-
7 making. Although both of these public-science collaborations are often said to lead to improved
8 environmental decision-making, evidence for these outcomes in the peer reviewed literature
9 remains sparse. We suggest that combining these fields has promise for developing community-
10 supported research leading to conservation action. To demonstrate this approach, we present the
11 infrastructure and use of a participatory modelling software called Mental Modeler
12 (<http://www.mentalmodeler.org/>), used with a citizen science web portal (www.citsci.org) that
13 allows citizen scientists, scientists, and managers to: (1) collaboratively define local conservation
14 issues of shared concern; (2) model and represent assumptions, evidence, and existing
15 information about these issues; (3) run scenarios to discuss potential research or management
16 options; and ultimately (4) co-develop citizen scientific research and conservation plans. Using
17 case study data from two community groups working on locally-defined issues related to land
18 management practices in the US, we demonstrate how coordinated learning through modelling
19 practices can lead to the development of self-organized and co-created conservation action. We
20 conclude that the development of online modelling tools holds strong promise for the fields of
21 both citizen science and conservation biology.
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23 **Keywords:** participatory modelling; citizen science; fuzzy cognitive mapping; public
24 participation in scientific research (PPSR).
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Introduction

Including the public in environmental monitoring, research and decision-making has been an area of growing research among conservation biologists (Reed 2008) and has implications for understanding the nature of many current pressing contemporary social and ecological issues (Crain et al. 2014). The interest in this area has given rise to several paradigms related to public participation in decision-making and more inclusive forms of conservation, including citizen science (Bonney et al. 2014) and participatory modelling (Voinov and Bousquet 2010). Although these areas of research share similar goals and provide a space for integrating the general public and specific stakeholders into the generation of scientific information, reviews of the literature in both fields indicate that the majority of citizen science projects and participatory modelling contexts are often not explicitly designed to lead to conservation action (e.g., Conrad and Hilchey 2011). We raise this issue and contend that with targeted educational training, motivated volunteer groups can play a larger role in conservation if afforded the opportunity to negotiate and represent their understanding of local environmental issues through modelling with scientists and, further, collect data that informs the revision of these models leading to an iterative process of hypothesis testing and model validation. We discuss how the strengths of citizen science and participatory modelling can be integrated under one program and present case study data working with two community groups in the US who engaged in two collaborative adaptive management projects focussed on local land management issues.

1.1 Citizen Science

The term ‘citizen science’ falls under the umbrella of public participation in scientific research 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 umbrella term citizen science generally refers to several forms of public contribution to scientific research, the type and degree of participation across different citizen science programs varies widely. Given a growing number of citizen science case studies in the literature (Jordan et al. 2015), researchers have begun to typify citizen science projects based on the degree to which the public is involved in the scientific process (Cooper et al. 2007; Bonney et al. 2009; Shirk et al. 2012). These general categories include (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 where citizens are provided opportunities to collaborate on project design and in data collection and analysis; 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 volunteers are engaged mainly to help increase data collection capacity (Bonney et al. 2009).

The bias in project design toward contributory citizen science projects is understandable, but may limit the type of contribution that citizen science makes toward conservation. For example, contributory projects provide clear benefits to researchers who can substantially increase data collection and analytical power that would not otherwise be possible. Additionally, contributory projects allow researchers the ability to maintain control of project design, including defining what questions are asked and how the data should be analysed. Indeed, some projects that require little training or low scientific reasoning skills to participate can engage hundreds of

thousands of volunteers, in many cases through crowdsourcing, which can generate hundreds of thousands of observations (Lintott et al. 2011). The popularity of contributory projects also aligns well with the predominant reasons for citizen participation which some researchers have found to be largely driven by a general interest in contributing to authentic scientific research (Wiggins and Crowston 2012) and social motivations like engaging in a community with similar interests (Raddick et al. 2010).

Although contributory projects have undoubtedly led to significant discoveries across many scientific disciplines, including conservation (Newman et al. 2012), the impacts of these contributions may be somewhat removed from the local-scale at which citizens participate and may not satisfy volunteers who are motivated to improve environmental quality (Wiggins and Crowston 2012). In fact, there are a growing number of more collaborative and co-created projects emerging from the literature (see Nicosia et al. 2014 and Ramirez-Andreotta et al. 2015) namely by groups of volunteers that are formed because of a specific research issue and not by contribution to science more generally. However, compared to contributory projects, it is not currently well understood how these more democratic forms of citizen science can be supported, how these processes should be structured, and what outcomes can be reasonably expected (Gray et al. 2012b). While many researchers have indicated that citizen science holds considerable promise for increasing the quality of environmental decisions and even contributing to social-ecological resilience (Shirk et al. 2012), empirical reviews of citizen science programs indicate that the data collected in a majority of projects may not lead to changes in management decision-making (Conrad and Hilchey 2011) much less tractable and measurable conservation outcomes. Further, of particular interest to conservation biologists, is capitalizing on those specific volunteer communities that are motivated to participate by an interest in stewardship. Such groups likely hold considerable promise, not only for contributing to large-scale conservation issues (Sullivan et al. 2014) but as a network of communities that seek conservation change at the local-scale, driven by an interest in place-based issues (Newman et al. *this issue*). Understanding the process that these groups undergo will likely provide evidence that citizen science can lead to changes in environmental decision-making however, to date, this hypothesis remains largely untested. Indeed, scientists and communities currently lack the tools and frameworks required to easily establish more collaborative and co-created citizen science projects (Gray et al. 2014a) which limits the conservation community's ability to incorporate stakeholders' knowledge, skills and manpower to address issues of both scientific and public concern.

1.2 Participatory Modelling

During the same time that citizen science has come to prominence, participatory modelling has also been a growing area of both academic research and applied practice. The justification for including stakeholders in scientific modelling practices 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 (Gray et al. 2015). This increased interest in participatory modelling has given rise to a range of stakeholder-centered modelling 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 modelling 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).

Similar to citizen science, researchers have recently begun to typify the benefits of participatory modelling through systematic evaluation of the growing number of case studies available. Such efforts identify trends in both the process and products associated with participatory modelling with implications for improved conservation decision-making. For example, Sandker et al. (2010) found that although there are several common tools associated with the practice of participatory modelling, including Bayesian methods, Agent-based modelling, and Systems Dynamic modelling among others, the largest contribution of engaging stakeholders in modelling 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 as a result of the modelling process, but this was largely dependent on types of stakeholders that were included in the process. In terms of the modelling 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 stakeholder 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). In a review of Bayesian network case studies, Duesphol et al. (2012) identified issues in terms of the cognitive loads associated with defining the conditional probabilities used to construct the models, reliability of expert knowledge, and a lack of satisfaction in the precision in model results. Others have also suggested that different modelling techniques may be more or less appropriate to employ given variation in the community engaged in the modelling process and the types of modelling practices that are useful for a given decision-making context (Gray et al. 2015).

Even though participatory modelling case studies are diverse, a consistent and clear benefit listed among all efforts comes in the form of structured social learning among those involved (Voinov and Bousquet 2010). Surprisingly, however, documenting the learning that takes place often takes a backseat to the model that is produced or documenting the process of engagement. Even when learning has been evaluated, some research has indicated that changing the way people think is a slow process. For example, Pala and Vennix (2005) evaluated conceptual change in students after participating in a systems dynamics course and indicated that even in formal settings, students were more likely to alter their structural understanding of systems rather than their underlying beliefs. In a review of six diverse participatory modelling case studies dealing with landscape management, Sandker et al. (2010) reported similar findings across a range of participants through standardized surveys. In the context of disaster planning, Henly-Shepard et al. (2015) by contrast, did report evidence of conceptual change among participants at the group-level by evaluating how the model produced by the community was revised iteratively over time. However this study did not focus on whether individuals within the community changed their understanding of the nature and dynamics of the environmental problem they were addressing.

When considered together, these findings highlight the importance of (1) prolonged engagement between scientists, managers and stakeholders as they engage in the modelling process; (2) the need to evaluate conceptual change among participants both at the group and

individual-level; and (3) understanding how the models produced (i.e. products) ultimately relate to decision-making or the plan of action that emerges from these collaborations.

1.3 Reconciling Citizen Science and Participatory Modelling for Collaborative Conservation

Although both citizen science and participatory modelling have provided useful frameworks, methods, and tools for engaging the public with environmental research, monitoring, and decision-making; there remain questions about how to leverage these areas for clear use in conservation beyond mere public engagement through outreach (Voinov et al. 2016). While reviews of both citizen science and participatory modelling have identified common trends, typologies of participation and gaps in our understanding of these fields, new approaches are needed that draw on research in both of these fields in project design to increase decision-making agency (Jordan et al. 2016). Documenting both the process and products associated with citizen science and participatory modelling will give credence to the often mentioned, but largely unsupported claims that these programs hold value to conservation decision-making, especially at the local scale.

To address some of the issues, we present the architecture and data from a citizen science program called Collaborative Science that includes web-based training, an embedded fuzzy cognitive mapping modelling 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 conservation science and management. Specifically, our program seeks to increase the degree of participation from citizen groups who are motivated by local environmental conservation, as well as the representation of local stakeholder knowledge, to increase the quality of conservation outcomes by allowing scientists, environmental managers and citizen scientists to: (1) collaboratively define conservation 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 that lead to measurable impacts. We suggest that such an approach will help lead communities toward conservation action, through structured learning that allows knowledge to be shared among participants leading to a standardized representation of a hypothesis that can be validated through data collection. Additionally, by attempting to evaluate the conceptual change in individuals and in groups engaged in these practices, we attempt to link evidence of learning to model representations and ultimately conservation plans that are co-created thereby addressing gaps in both the citizen science and participatory modelling literatures.

Methods

2.1 Collaborative Science Project Design

The Collaborative Science program (Figure 1) is a series of web-enabled tools that include (1) ecological and adaptive management training curriculum; (2) a fuzzy cognitive mapping software which allows volunteers and scientists to define a problem context that represent their knowledge and run scenarios; and (3) a web-based portal which allows volunteers and scientists 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 two groups in Virginia, USA, in our collaborative space to develop an

environmental management project co-developed by a volunteer group working with professional land managers. Next, using a case study analysis of individual and group models created by participants in the program, we demonstrate how collaborative modelling activities led to a focus on the conservation issue and the dynamics of the conservation issues. Finally, we discuss the community driven management plans and outcomes that emerged from the two volunteer groups as evidence of conservation action.

[Figure 1]

2.2 Conservation Training

We chose to focus our project 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 of project and who were also sufficiently willing and interested in increasing their level of participation in local environmental management. Although we describe the use of these tools in terms of higher degrees of citizen participation, the learning tools are flexible and can be used by either citizens or professionals to structure and implement citizen science projects.

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 to conserve 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 continuing education 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 (Blanton et al. 2014). Many are retired with at least some previous experience with natural resource conservation.

2.2.1 Content Area Instruction

The goal of our learning environment is to prepare participants to engage in collaborative or co-created citizen science projects across regions (see Cooper et al. 2007; Bonney et. al. 2009; Shirk et al. 2012). The training content design, therefore includes an online, asynchronous program focused on providing information on ecology, conservation, the use of models in scientific reasoning, basic statistics, and the use of the Mental Modeler software tool. We also provide an overview of the adaptive land management process. This content is given in a series of 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.

The ecology content focuses on basic ecological principles, including energy and food webs, nutrient cycles, population dynamics, interactions, community structure, and ecosystem services (note in our current iteration of the project, all material is optional). 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 delivered in person and was selected to focus the group into developing a conservation strategy based on the needs and interests of its members. This section encourages discussion about 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.

2.2.2 Practice-Oriented Instruction

The practice-oriented instruction focuses on using the software, Mental Modeler and web-based tools CitSci.org (see below) 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 (Note that this is different in our current iteration of the project website). 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.

2.3 Mental Modeler Software

Embedded as part of the training is a cognitive mapping software called Mental Modeler (www.mentalmodeler.org, Gray et al. 2013). 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 develop 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. 2015).

Mental Modeler is based on Fuzzy Cognitive Mapping (FCM) (Kosko 1986; Özesmi and Özesmi 2004) and is 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.

2.3.1 Concept Mapping Interface

The concept mapping interface allows stakeholders to structure the dynamics of an environmental problem using a conceptual space by defining variables or nodes that comprise natural resource systems and defining the relationships between these variables. By first adding variables (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 variables hypothesized that are related to understanding the system or problem that is being addressed.

After variables have been defined, the relationships between variables can be added by using directional arrows which indicate the amount of influence one component can have on another, called edge relationships. Variables 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 variables 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 variables. 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 2).

[Figure 2]

2.3.2 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 variables 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.

2.3.3 Scenario Interface

The third interface in our software is the Scenario interface where artificial scenarios on the conceptual model can be run and compared. The scenario interface indicates the amount of relative change in the concepts 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 conceptual scenario each concept included can be set at a value between qualitatively defined states of +++ (strong negative change) and --- (strong positive change). Relative change in the concept map is displayed as a bar graph to indicate how concepts might react under a given scenario which is viewed compressively as a system state change. This interface uses matrix algebra algorithms described by Ozesmi and Ozesmi (2004) and elsewhere (Gray et al 2013, Gray et al. 2015) and visualizes systems states under scenarios by subtracting the steady state from the scenario state.

2.4 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 conceptual 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 (Figure 3) 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. Thus, after participants conceptually model the dynamics of the conservation problem to be addressed, the model can be used to guide data collection plans in CitSci.org. 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 (Fig. 3).

[Figure 3]

Case Studies

To demonstrate the use of our tools in a co-created citizen science program, we present data collected from two groups of the Virginia Master Naturalists, working with professional land managers and scientists in Virginia. Both Master Naturalist chapters that enrolled in the program followed the same basic process that included the following steps facilitated by a professional scientists. These steps included:

1. Volunteer hybrid-online and in-person training
2. Identifying the land management study area
3. Scoping process with land managers to identify conservation issues
4. Initial individual modelling of the issue
5. Collaborative modelling of the conservation issue and model refinement
6. Data collection and management plan design

First, all volunteers engaged in the online training modules mentioned above to orient them to the project and gain a basic understanding of ecological principles, the role of modelling in scientific research and be introduced to the adaptive management framework. Second, volunteers worked with a project scientist to discuss local land management issues that they would like to address. Third, the conservation issues discussed were then brought to relevant land managers and further debated. Fourth, all volunteers were asked to develop an individual model in the Mental Modeler software that represented their understanding of the dynamics of the land management issue that was collaboratively identified. Fifth, volunteers' individual models were aggregated into one group model by project scientists using qualitative aggregation techniques (see Ozesmi and Ozesmi 2004) and discussed at an in-person workshop. During this workshop the model concepts and relationships were collaboratively discussed to develop a representation that could be used as the basis for identifying hypotheses to be tested, research questions, a data collection plan, and to guide the overall project design. Although the modelling activity was based on conceptual understanding of the problem, explicit discussions of how concepts included in the concept maps might be measured facilitated volunteer thinking about what variables might be measured in the field.

In addition to these steps, two volunteers, one from each project, were also asked to develop second individual models after the group modelling exercise so that these post models could be compared to their initial models to uncover whether their understanding of the land management issue changed as a result of these collaborations. Below we describe two case studies in which participants were engaged. Next, we describe the refined group models that each group developed. We then discuss the pre and post models collected from two participants at the beginning of the project and after collaboration. Finally, we discuss the refined group models that were created and discuss their relationship to design of their management projects.

Case Study 1: Managing the Red Cockaded Woodpecker Habitat

In the first project, seven participants in one Virginia Master Naturalist chapter in southeastern Virginia enrolled in a hybrid class with online content presentation and in person discussion over a three-week period in 2013. Participant concerns over habitat quality of the endangered Red Cockaded woodpecker, along with a prior relationship with land managers employed by The Nature Conservancy, led them to develop a project investigating *Microstegium vimineum* (Japanese stiltgrass) control methods. Their project goal was to measure the relative effectiveness of five different treatment regimes (burning, chemical, mechanical, mechanical followed by chemical, burning followed by chemical) on seedling recruitment in subsequent years. Participants designed an experiment to show evidence of the extent of the incursion in the habitat and marked 72, 1 m² plots within four different grass patches to identify the best invasive management action.

Case Study 2: Water Quality and Cattle Ranching

In a second project, 16 Master Naturalists in central Virginia had concerns over water quality in a stream through a development where some volunteers owned property with agricultural and conservation easements. The development includes working agricultural land with cattle grazing. Previously-installed fencing excluded cattle from wallowing in streams, and members were curious to measure the effect of these buffers on water quality, and to use that data to apply for funding from the nearby Soil and Water Conservation District to install additional fencing and wells. Based on the group's research plan, three participants received

training from the Virginia Department of Environmental Quality on water quality testing using readily available Coliscan Easygel™ kits. Participants measured water quality at five points within the property once a month for 18 months. These areas include where the stream enters the property, previously buffered streams, and three unbuffered sites. Property owners were awarded a 100% cost share from the conservation district to install four miles of fencing and drill three wells, approximately \$200,000 worth of supplies and labor.

Based on continued testing, fencing out the cattle has significantly improved the water quality in the stream such that there is no longer any significant *E. coli* contamination. In addition, the fencing has presented an opportunity to take advantage of a 35 feet in width of riparian buffer on each side of the stream. The group currently is doing plantings to improve the quality of the buffers and planning an interpretive trail through the buffers that will be used with visiting youth and adult groups for environmental education. The improvement in the water quality and the follow-up project are evidence of conservation outcomes resulting from this project.

3.1 Group Models and Data Collection Plan in Citsci.org

After initial discussions and after initial models of the land management issues were collected from all participants, they were aggregated during an in-person workshop and refined for discussion. FCM model aggregation has been shown to be a successful technique for representing collective understanding of environmental issues that is useful for discussion and planning (Gray et al. 2014; Nyaki et al. 2014). These group models were analyzed for their several structural characteristics using common network-based metrics (see Özesmi and Özesmi 2004; Gray et al. 2014) to gain an understanding of how each volunteer group collectively understood the dynamics of the conservation problem. A particular strength of FCM is that they are a semi-quantitative and parametrized form of concept mapping, which allows for inferences about group knowledge to emerge (Özesmi and Özesmi 2004; Gray et al. 2012; Nyaki et al. 2014). The metrics used included counting the number of variables, number of relationships, the most central variables to overall network structure, model density, model complexity as well as the number of driving, receiving and ordinary variables (see Özesmi and Özesmi 2004 and Gray et al. *in press* for a full discussion of FCM network metrics).

These FCM network metrics were selected since they provide an indication of how individuals or groups perceive the system to be structured. For example, the number of concepts included in a model indicates the system composition (and boundaries) while the relationships between concepts define weighted and directional influences between these system components (Nyaki et al 2014). All concepts in a model can be categorized in one of three ways based on how they are defined in the conceptual model: as driving components, receiving components or ordinary components (Ozesmi and Ozesmi 2004; Gray et al. 2014). The component category is determined by converting each model into a matrix, listing all concepts on two axes, and using the weights (in absolute values) between concepts to calculate its overall outdegree (degree of influence a concept has on other concepts) and its indegree (degree to which other concepts influence a particular concepts). In the matrix format, facilitated by the Mental Modeler software, driving concepts can be identified as concepts that have positive outdegrees and zero indegrees (only weighted arrows going out from a concepts) while receiver concepts can be identified as concepts with a zero indegree and positive outdegree (only weighted arrows going into a concept). Ordinary concepts have both non-zero outdegree values and non-zero indegree values. In addition, the overall centrality of a concept to system structure can be calculated by

summing the outdegree and indegree, giving each concept a relative ranking to its "importance" in terms of its network structure. Density within a model can be calculated by determining the number of relationships represented compared to the total number of possible relationships in the matrix (number of relationships defined/number of concepts defined x number of concepts defined). Finally, complexity scores can be calculated to indicate the degree to which the outcomes of driving forces are considered in terms of the ratio of driving variables to receiving variables (Gray et al. 2012; Gray et al. 2014).

The final woodpecker model included 23 concepts with 32 connections between them which included 11 driving concepts, two receiving concepts and 10 ordinary concepts (Figure 4A). The most central concepts included Stiltgrass abundance, Woodpecker habitat and the Stiltgrass seedbank. The concepts considered to be driving the dynamics of the issue include post and pre-emergent pesticides and wet conditions. Woodpecker abundance and wildlife were considered to be the most sensitive and impacted.

The final water quality model included 20 concepts with 61 relationships between them. Their model included three driving concepts, three receiving concepts and 14 ordinary concepts (Figure 4B). The most central concepts to the network included stream water quality, livestock and drinking water for livestock. Funding sources, rainfall, and the local management commission were considered major drivers while fish macroinvertebrates and land owners were thought to be most impacted (Table 1).

[Figure 4]

3.2 Measuring Conceptual Change in Understanding of the Conservation Issue

Below, we provide examples of concept maps collected from two individuals, one from each of our case study projects (Figs. 5 and 6). We compared the individual model collected by convenience from one participant in each group to better understand conceptual change pre and post involvement in collaboration with land managers and other participants. This was done in an effort to provide evidence of conceptual change (e.g. learning) as a result of collaboration on the individual-level.

[Figure 5]

[Figure 6]

Comparison of the individual models collected at the start of the project and again after collaboration with other volunteers and scientists showed evidence of learning as a result of participation in the program (Table 1). Some of these changes in their models indicated similar trends in their understanding of their respective conservation issue while other measure indicated some key distinctions.

In terms of similarities, both volunteers showed an increase in the number of concepts (potentially measurable and operationalized as variables) considered important to the dynamics of the problem. Similarly, both individuals increased their understanding of what they consider drivers of the conservation issue and an increase in the variables in the system that were impacted, as evidenced a change in the number of receiver variables. Additionally in both cases model density decreased after collaboration, as measured by the number of relationships represented compared to the total number of relationships possible (N variables x N variables).

This change in model density indicates that both volunteers refined their understanding of their issue over time.

In terms of differences, pre and post analysis of these sample models show that while the individual participating in the woodpecker habitat project vastly increased their understanding of the number of connections between concepts (from 19 to 48 relationships represented), the individual participating in the water quality project decreased the number of relationships shown (from 19 relationships to 17 represented). Additionally, while the woodpecker habitat volunteer's model indicated a higher complexity score post collaboration, the water quality volunteer indicated a slight decrease in complexity. The reasons for this change in complexity is unclear, but it is likely related to the water quality volunteer starting the project with a considerably more complex model compared to the initial woodpecker model which represented a very linear way of thinking about the conservation issue upon enrollment in the program. These differences indicate that prior knowledge of the conservation issue may impact learning and suggests that there may be differences in learning progressions in both citizen science and participatory modeling projects mediated by the knowledge heterogeneity among participants at the start of the project.

[Table 1]

3.3. Data Collection and Conservation Management Plans

Both projects used the models to develop management plans, but toward different ends. Specifically, the woodpecker model group decided to test hypotheses (Fig.7) regarding best practices for the management of stiltgrass while the water quality group decided that seeking further funding (\$200,000 as mentioned previously) to implement water quality projects was the most effective way to deal with the issue.

The implementation of both of these management strategies is represented by the change in the structural metrics of each group's model. The stiltgrass group implemented an experimental design to measure the relative effectiveness of alternative control measures. Accordingly, the dependent variables integral to their experiment, "rate of stiltgrass growth" and simply "stiltgrass," became the central receiving variables (Table 1). Likewise, the independent variables in their experimental design (fire, herbicides, and mechanical control such as "mowing" and "pulling"), either appeared in the post model after being absent in their original models, or became central drivers in the post and group models. Compared to earlier models that focused primarily on the basic ecology of the system and the interactions between sun, water, fire, the invasive grass, and the pine ecosystem, later models represented several alternative hypotheses related to invasive plant control.

While the stiltgrass group was primarily driven to hypothesis-testing, the water quality group was focused on implementing established best practices in agricultural water quality improvement: restricting cattle access to streams and establishing riparian buffers. Accordingly, the cost of this plan was the primary roadblock, and it became the most central and most significant driving variable in the post plan, after being a peripheral variable in earlier plans (Figure 7). As one volunteer noted late in the process, after realizing the cost of improving water quality would include several miles of fencing and several new wells, "It all comes down to who's paying for it." Evidence for this change in understanding on the individual-level can be found in the group model during the change in focus from "cows" in the first model to "cost" in their second model, and a change in the group model that represented "cost" as the most central

driving component. Discussions around the funding sources as the most significant driver led to discussions about how to appropriately influence the overall system dynamics that allowed motivated volunteers to seek out funding for their project as the most effective way to address issues of water quality.

[Figure 7]

Discussion

Both citizen science and participatory modelling often rely on (1) structuring environmental problems or scientific questions in a manner that answers a question of either scientific or social concern and (2) involving collaboration with both the public and professional scientists in this endeavour. Whether these public-science interactions are designed to be more top-down (i.e. contributory projects or participatory modelling efforts where models are simply reviewed by stakeholders) or bottom-up (i.e. co-created projects or iterative collaborative modelling practices), both approaches bridge intersecting communities of practice by creating shared terminologies and attempt to standardize both knowledge about an issue and the process of inquiry (Voinov et al. 2016). Research has demonstrated that collaborative knowledge construction can be effectively supported when conversational and conceptual representations are made explicit (Suthers 2008; Suthers et al. 2008). Computer tools provide unique affordances that can support the new kind of learning community we are trying to create in this project. In particular, Bryant et al. (2005) note that both moving information and connecting people support the broader function of distributing shared information in authentic ways among both people and ideas, which is a hallmark of both citizen science and participatory modelling.

Critical to our project is the development of a shared conceptual model, which is essential to community learning, problem-solving, and environmental decision-making (Voinov and Bosquet 2010). In the context of collaborative and co-created citizen science, the need to collaboratively make decisions is often necessary (e.g., Bonney et al. 2009); making participatory modelling a valuable tool. Further, the ability to engage in data collection partnerships (i.e., citizen science) can enhance the capacity of project participants to make decisions because uncertainty in model parameters will likely be lessened. In this manner, participatory modelling and citizen science practices work hand in hand to create resource management protocols that are stakeholder inclusive and nested in sound science. We believe these links among modelling, data gathering, and adaptive management foster in volunteers a capacity to enact their conservation goals in ways not previously utilized. Although these approaches to participatory science and decision-making are clearly complementary, it is only recently that researchers working at the intersection citizen science and environmental modelling have begun to link the two fields with recommendations for integration. For example, Voinov et al. (2016) recently called for distinctions to be made between general citizen involvement or participation (e.g. public involvement in asking or declaring needs, preferences, or prejudices) and (b) the involvement of people in the pursuit of technical or scientific knowledge. Although both of these dimensions are routine forms of public participation in environmental decision-making, these authors argue that producing knowledge in true participatory forms requires that stakeholders and citizens are not just used as passive sensors, but rather are instead active participants in “checking, assessing, or commenting on scientific observations”. Although linking the fields of participatory modeling and citizen science is hypothesized to operationalize

social and environmental benefits previously identified in the literature (see Shirk et al. 2012) programs, processes and software tools that are explicitly designed that draw on the strengths from both fields have been slow to emerge. Our program, tools, and engagement with stakeholders seek to address this gap by providing design features and preliminary data that demonstrate how a suite of cyber-enabled tools might be used to structure and communicate understanding of environmental issues leading to more direct forms of conservation actions between communities of practice.

Our approach in this project involved using software designed for participants with educative, collaborative, and self-paced learning tools embedded in an adaptive management framework. Using this approach, however, required resources in terms of time and money, which were expended upfront and prior to participant engagement. This allowed for ready-made and user-friendly tools that helped us to reduce frustration with the online learning environment. For others seeking to do so, we stress that the process of modelling needs to be central to the projects in which participants are engaged. Doing so will help to avoid participant ambivalence about modelling, which may at times seemed 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.

Although the volunteers' data collection is still on-going, we measured a significant increase in participants' confidence in the potential effectiveness of their conservation plan pre and post the learning and planning process. Additionally, all participants reported that they would engage in a project like this again. Further, we demonstrated that merging participatory modelling and citizen science could provide improvements to management goals, while maintaining participant satisfaction and engagement in science. Finally, while we are still early in the process of working with participants, we have enough evidence to suggest that citizen science and participatory modelling are not only similar in goals, but can be similar in practice.

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FIGURES AND TABLES

Figure 1. Screenshot of www.collaborativescience.org homepage.

Figure 2. Screenshot of Mental Modeler software Concept Mapping interface that includes (A) defined variables (B) directional edge relationships and weights defined between variables (C) notes about variables and relationships to be included as evidence for inclusion in the model and (D) proposed unit of measurements for variables.

Figure 3. Screenshot of www.citsci.org homepage.

Figure 4. A. Final woodpecker habitat project group model. B. Final water quality and cattle project group model.

Figure 5 A. Concept map collected from one volunteer that represents individual understanding the woodpecker habitat issue collected at the start of the project. B. Concept map collected from the same individual on the woodpecker habitat issue collected after collaborations with other group members and managers.

Figure 6 A. Concept map collected from one individual that represents individual understanding of the water quality conservation issue collected at the start of the project. B. Concept map collected from the same individual of their understanding of the water quality conservation issue collected after collaborations with other group members and managers.

Current questions:

What is the name of the surfactant that is approved for use around water. Where can we get it?

What is the exact mechanism of pre-emergent herbicides?

Is there a way to accelerate *M. vimineum* germination in order to reduce the seed bank in the soil?

Next Steps

Decide on a dependent variable.

Decide on which treatments and plots to use.

None of the above designs need a statistician, as we would simply compare the effect of each treatment on the dependent variable. A statistician only needs to be consulted if we decide to mix large and small plots into the same experimental design. I do not recommend this. We can treat the small plots and record that data and only focus our experimental design efforts on the large plots.