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Can citizen science enhance public understanding of science?

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Abstract

Over the past 20 years, thousands of citizen science projects engaging millions of participants in collecting and/or processing data have sprung up around the world. Here we review documented outcomes from four categories of citizen science projects which are defined by the nature of the activities in which their participants engage – Data Collection, Data Processing, Curriculum-based, and Community Science. We find strong evidence that scientific outcomes of citizen science are well documented, particularly for Data Collection and Data Processing projects. We find limited but growing evidence that citizen science projects achieve participant gains in knowledge about science knowledge and process, increase public awareness of the diversity of scientific research, and provide deeper meaning to participants' hobbies. We also find some evidence that citizen science can contribute positively to social well-being by influencing the questions that are being addressed and by giving people a voice in local environmental decision making. While not all citizen science projects are intended to achieve a greater degree of public understanding of science, social change, or improved science -society relationships, those projects that do require effort and resources in four main categories: (1) project design, (2) outcomes measurement, (3) engagement of new audiences, and (4) new directions for research.

Keywords
lay expertise, participation in science policy, public participation, public understanding of science, science attitudes and perceptions, science education, scientific literacy

1. Introduction

In February 2015, the Citizen Science Association (CSA)—an organization of professionals who design, implement, and study citizen science projects—held its first-ever conference in San Jose, California, attracting more than 600 attendees from 25 countries. In April, representatives of the European Citizen Science Association (ECSA) met in Leipzig, Germany, to plan an inaugural

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ECSA meeting for winter 2016. In July, the Australian Citizen Science Association (ACSA) held its inaugural conference in Canberra.

What is citizen science and why has its practice become so widespread?

Some people equate citizen science with a movement to democratize science. This idea likely stems from the 1995 publication of Alan Irwin's book, *Citizen Science: A Study of People, Expertise, and Sustainable Development* (Irwin, 1995). The goal of citizen science espoused by Irwin is to bring the public and science closer together, to consider possibilities for a more active "scientific citizenship," and to involve the public more deeply in dialogue and decision-making around issues related to risk and environmental threat.

Other people equate citizen science with public participation in scientific research, in particular, with members of the public partnering with professional scientists to collectively gather, submit, or analyze large quantities of data. This definition stems in part from adoption of the term—also in 1995—by the Cornell Lab of Ornithology, whose staff sought a name for the lab's rapidly growing assemblage of projects involving large numbers of individuals collecting data focused on birds (Bonney, 1996). These projects were designed to amass data that would help researchers study bird biology and ecology across North America and were born from the long history of amateur naturalists recording and compiling data on flora and fauna that began in the United Kingdom a century earlier.

Owing largely to the power of the Internet, this latter definition of citizen science—which was added to the Oxford English Dictionary in 2014[1]—has become increasingly widespread. Over the past 20 years, thousands of projects engaging millions of participants in collecting and/or processing data have sprung up around the world. Project topics range from astronomy to zoology, and intended project outcomes are many and diverse. Typically, projects focus on answering specific scientific questions or on gathering data that can be used to influence public policy. However, because significant funding for citizen science originates from the Advancement in Informal STEM Learning (AISL) program of the US National Science Foundation (NSF), science education is an important or primary goal for many projects.

The perceived educational potential of citizen science leads to many questions. Can engaging in active scientific investigations help citizen science participants learn about the subjects they are investigating or understand how scientific investigations are carried out? Can participation in authentic science change attitudes or behaviors toward science? Can participants learn how to carry out scientific investigations on their own? If a participant learns how research is conducted—that scientific investigation involves observations and trials, controls and correlations, repetitions and revisions—then might that individual be able to understand and evaluate scientific claims and conclusions encountered in the course of daily life?

Concurrently, the notion of "Public Understanding of Science" (PUS) has evolved from discussions of a public deficit in science knowledge and attitudes to recognition of the need to increased participatory input (Bauer, 2009). Thus, as the citizen science field continues to mature and its participants engage in deeper and more complex efforts, additional questions emerge. Does citizen science empower communities and individuals to improve their well-being? Does citizen science engage underserved audiences (not just those already interested in science) in experiences that are meaningful to their lives? Does its practice move us from a one-way deficit model of public understanding to a multi-way dialogue of public engagement (Stilgoe et al., 2014)? Can citizen science play a central role in current notions of PUS as deliberative, participatory, and important for fostering science-in-society relationships? Is the explosion of citizen science around the world truly democratizing science in ways that Irwin envisioned in 1995?

2. Overview of citizen science accomplishments

To review the extent to which citizen science is impacting PUS—and perhaps science and society relationships—we have chosen to consider four broad categories of citizen science which all fall within the broader public participation in science framework. Specifically, we examine (1) Data Collection projects; (2) Data Processing (categorization, transcription, interpretation) projects; (3) Curriculum-based projects, which may take place in schools or in “informal” youth-development settings; and (4) Community Science projects. Note that we are not proposing a new typology for citizen science. Rather, for the purposes of a comprehensive review, we are examining categories of citizen science defined by the nature of the activities in which their participants engage.[2] We hasten to add that none of these categories is exclusive—for instance, Curriculum-based projects can include both data collection and data processing, and Community Science projects typically involve participants in data collection. However, the manner in which participants in these four project categories engage in scientific activities can be significantly different, resulting in opportunities for the four types of projects to play varied roles in PUS for participants and for science at large.

Data Collection projects

Citizen science is often used to describe projects for which volunteers—who may or may not have any formal training as scientists—collect data that can be used in organized scientific research. While amateur involvement in natural history investigations began as long ago as the seventeenth century (Miller-Rushing et al., 2012), at the time that the Lab of Ornithology began using the term ‘citizen science’ in the mid 1990s, public data collection efforts were still relatively few in number, at least in the United States. The National Audubon Society’s Christmas Bird Count had begun in 1900; the US Fish and Wildlife Service’s Breeding Bird Survey and the Cornell Nest Record Card Program were both born in 1965; and several localized projects had been formed to monitor the quality of water in lakes, rivers, and streams. But the idea that the public could make a meaningful large-scale contribution to scientific investigation was still in its infancy.

Two decades later, public data collection projects number in the thousands and their participants number in the hundreds of thousands. Worldwide, projects cover topics ranging from native bees to invasive plants and from urban birds to swamp-dwelling frogs (see www.citizenscience.org and www.scistarter.com). Some projects are hypothesis driven, collecting data to address a specific research question. Others focus on environmental monitoring more broadly.

Theobald et al. (2015), writing in the pages of *Biological Conservation*, have provided the field with a groundbreaking review of the impacts of this form of citizen science, which generally fits into the “Contributory” category described by Bonney et al. (2009) and updated by Shirk et al. (2012). The authors identified 388 unique biodiversity-based projects and estimate that between 1.36 and 2.28 million people volunteer for these projects each year, with each participant spending an average of 21–24 hours collecting data. The authors further estimate the annual range of in-kind contribution as between US$667 million and US$2.5 billion. They note that these figures likely represent a minimum estimate for biodiversity citizen science worldwide, as their sampling was restricted to projects that reported in English and were listed in major online citizen science clearinghouses.

They also determined, primarily through a search of the Web of Life, that these projects have yielded a total of 446 scientific publications. (The actual number of published articles based on publicly collected data is much higher, and the number grows substantially each month.) Furthermore, results of citizen science projects have been published in high-profile scientific journals, including *Bioscience, Conservation Biology, Trends in Ecology and Evolution*, and *Proceedings of the National Academy of Science.*

It is clear that public data collection projects are yielding important scientific results. Are they also yielding increased understanding of science for their participants? In fact, evidence for such effects is limited. Very few efforts to determine or measure learning or other social outcomes from participation in citizen science have been undertaken, for several reasons. First, assessing such outcomes from public programs is always challenging. Established metrics and techniques are few and far between, and evaluators who can develop and deploy such tools are expensive, especially for projects operating on shoestring budgets. Second, the concept of PUS can be defined and measured in so many ways that a beleaguered project leader is hard-pressed to know where to start.

Several papers published over the past few years do show gains in participant knowledge of scientific content. For example, participants in The Birdhouse Network (TBN), one of the earliest citizen science projects to be funded by the US NSF, placed nest boxes in their yards or neighborhoods and collected data about the birds that bred in them during spring and summer. Participants in the early years of this project showed statistically significant increases in their knowledge of bird biology (Brossard et al., 2005).

Other projects that have measured gains in participant knowledge of science content include the National Institute of Invasive Species Science (NISS) program, whose participants showed small increases in content knowledge of invasive species, global positioning system (GPS), and vegetation monitoring when using context-specific measures (Crall et al., 2012), and participants in the Smithsonian Institute's Neighborhood NestWatch, who learned about bird nesting behavior (Evans et al., 2005). Also, hikers who were trained to follow a protocol for collecting data about invasive plants, and who subsequently gathered to analyze data and discuss responsible environmental behavior with respect to invasive plants, reported increased ability to recognize invasive plants and increased awareness of the effects of invasive plants on the environment (Jordan et al., 2011).

Data Collection projects have also attempted to measure changes in participant understanding of scientific process. Few have been able to demonstrate such change. One that showed some indication of success was the Cornell Lab of Ornithology's 1992 Seed Preference Test. Participants in this project followed a simple experimental protocol as they provided three types of seeds in rotating locations and counted the numbers of birds that came to each seed type. Evaluators of this pre-Internet project showed that many participants were actively engaged in the experimental process. When they encountered problems, they used their knowledge of birds and bird behavior to adapt the procedures, thereby using appropriate scientific processes and principles in making personal decisions (Trumbull et al., 2000).

Few other projects have demonstrated increased participant understanding of scientific process. Some participants in TBN asked original questions and some of these questions were refined and developed into new TBN studies, and some TBN participants set up their own experiments and shared results with email discussion groups and project scientists. However, project evaluators were not able to measure increased science process knowledge overall (Brossard et al., 2005). And participants in the invasive plant training mentioned above did not increase their understanding of how scientific research is conducted (Jordan et al., 2011).

Data Collection projects also have attempted to assess changes in participant attitudes and behaviors toward science. Participants in TBN showed little to no change in attitude as a result of project participation (Brossard et al., 2005). In the aforementioned NISS program, evaluators found no changes in desired behaviors related to improving habitats, engaging in political processes, or feeling empowered to make changes. They did find that providing training for participants altered their intentions to behave differently in the future with respect to pro-environmental activities such as volunteering for environmental organizations, attending community events, removing local invasive species, and educating others about them (Crall et al., 2012). And adult mentors involved with the Monarch Larva Monitoring Project (MLMP), based at the University of Minnesota, note that the participating youth appreciated the social aspects of the program, engaging in “science bonding” (Kountoupes and Oberhauser, 2008).

The fact that participants in some public Data Collection projects achieve some measurable gains in knowledge about science content or process is a hopeful finding. That participants do not seem to demonstrate noticeable changes in attitudes or behaviors is cause for reflection. Many factors might account for this finding. One likely reason is that participants in many projects, because they are self-selected, already have positive attitudes toward science when they start the projects. In evaluating TBN, Brossard et al. (2005) were able to demonstrate that participants entered the project with very positive attitudes toward science compared with the “average public.” Yet another factor could relate to project design: often Data Collection projects are not constructed, whether intentionally or unintentionally, to achieve specific science learning and understanding outcomes. We will return to these points in the discussion.

Data Processing projects

While development of the Internet has greatly facilitated citizen science projects based on data collection, the Internet also has enabled an entirely new category of citizen science focused on data processing, sometimes referred to as “crowd science.” In 2007, a project called Galaxy Zoo began enlisting the public in classifying images of space that were captured by the Hubble Space Telescope. In the project’s first year, more than 150,000 people classified more than 50 million images, a task that scientists never would have been able to accomplish on their own even with the aid of complex computer algorithms. Following this lead, citizen science projects that were focused on data transcription, categorization, management, and interpretation quickly became popular as new projects were developed to explore the surface of the moon, to model Earth’s climate using historic ship logs, and to map neurons in the human brain. Participants in these projects, although not collecting data of their own, contribute to scientific discovery by helping to examine and analyze what would otherwise be unmanageable amounts of information. These types of projects generally fit into the “Contributory” type of citizen science (Bonney et al., 2009) but were not described in the 2009 typology because they were just coming into existence at the time that it was developed.

Another recent review of citizen science projects, this one in the *Proceedings of the National Academy of Sciences* (Sauermann and Franzoni, 2015), examined contribution patterns of seven different crowd science projects hosted on the platform Zooniverse.org, which is currently the largest aggregator of such projects and is host to Galaxy Zoo. These researchers demonstrated that Zooniverse projects have supplied a large quantity of data at relatively low cost, concluding that “unpaid volunteers who are driven by intrinsic or social motivations may indeed enable crowd science organizers to perform research that would strain or exceed most budgets if performed on a paid basis.” They estimate that these seven projects yielded about US$1.5 million worth of data (paid at US$12.00 per hour) over their first 180 days of life. And many of these data points are contributing to scientific discoveries. For example, Zooniverse projects have already yielded more than 50 peer-reviewed articles on topics ranging from galaxies to oceans (Smith et al., 2013).

Like data collection citizen science projects, many Data Processing projects are intended to achieve scientific goals while helping participants increase their understanding of science by engaging in the process of science. However, at this point in the evolution of the citizen science field, there appears to be even less evidence for development of participant understanding of science through engagement in Data Processing projects than through engagement in Data Collection projects.

One paper by Zooniverse researchers briefly mentions how Galaxy Zoo participants go beyond data management and engage in activities that could help to develop PUS (Fortson et al., 2012). The researchers explain that the goal of the project was to build a community of volunteers, and

> Galaxy Zoo forums and blogs show that citizen scientist volunteers wanted to do much more than classify objects … (they) set up several projects of their own using Galaxy Zoo infrastructure or methods, (so) citizen scientists have become research collaborators.

Evaluation also has been conducted for a project called "Citizen Sky," which combined data classification with online data collection. The project team measured changes in participants' overall attitudes toward science and in their epistemological beliefs regarding the nature of science. After participating for 6 months, those surveyed showed significant increases for both of these measures. However, participants also showed a significant drop in their science self-efficacy or their confidence in their own scientific knowledge and ability. The project team suggests that the drop in confidence could stem from growing awareness of how much there is to learn (Price and Lee, 2013).

Certainly, there is significant potential for Data Processing projects to contribute to PUS. But there are challenges. The analysis by Sauermann and Franzoni showed that although the amount of data processed by citizen scientists is significant, a small number of contributors make a large share of the contributions, a pattern that has been shown in other online efforts such as Wikipedia, as well as in some Data Collection projects. In fact, the researchers found that most participants contributed only once and with little effort, leaving the top 10% of contributors responsible for almost 80% of total classifications.

These findings suggest that Data Processing projects are not yet having a huge impact on PUS, but that they might be important for increasing public awareness of the kinds of new scientific research going on in the world and for providing opportunities for individuals to provide deeper meaning to their hobbies. Sauermann and Franzoni do point out that their analysis focused on projects that rely primarily on users' intrinsic motivations, and that other crowd science projects that are more gamelike—such as Foldit, EyeWire, or Phylo—may show different types and levels of participation outcomes.

Curriculum-based projects

A third category of citizen science is Curriculum-based projects. These are typically developed for K-12 audiences but often are used with other types of organized groups such as 4-H or other after-school programs. Many curriculum projects involve youth, supervised by educators or other adults, collecting and submitting data to a larger, "parent" citizen science project, and often such projects are aligned to state and/or national science standards. Examples include BirdSleuth, which contributes to the Cornell Lab of Ornithology's citizen science projects (www.BirdSleuth.org); Monarchs in the Classroom, which contributes to the Monarch Larvae Monitoring Project (www.monarchlab.org); the Nature's Notebook curriculum, which contributes to the National Phenology Network's Nature's Notebook (www.usanpn.org/educate/nn_curriculum); and Global Learning and Observation to Benefit the Environment (GLOBE), an international citizen science program engaging students in Earth science and global environmental monitoring. Other Curriculum-based projects are stand-alone programs that target particular research questions and collect important scientific data but which are intentionally designed to achieve specific educational goals for youth, such as Vital Signs (www.vitalsignsme.org) in Maine and LIMPETS (http://limpetsmonitoring.org/) in California. The key feature of Curriculum-based projects is the structured, scaffolded nature of the training, materials, and program support that facilitate the participation of youth and families.

Trautmann et al. (2013) explored the potential for curriculum-based citizen science and provided overviews of projects and lesson plans. These authors note that for many Curriculum-based projects, special attention is paid to designing youth-friendly data visualization platforms that allow participants who have collected and submitted data to view, and sometimes manipulate, their data within a broader context of data submitted by others. While not unique to Curriculum-based projects, data visualizations can provide support for participants to explore and ask questions of their data, which can lead to a robust scientific inquiry process.

As an example, BirdSleuth was developed through funding from the US NSF, and an early version of the curriculum received summative evaluation. The final evaluation report showed that students who participated in the project demonstrated increased knowledge of bird biology, communication, and identification. They learned to use a field guide as a tool for obtaining information about bird species. Students' definition of hypothesis became more refined, and they showed understanding of key features of scientific investigations and the nature of scientific research. Overall, they enjoyed the curriculum and felt that they would like to count and study birds again in the future (Thompson, 2007).

The GLOBE project, jointly sponsored by the US National Aeronautics and Space Administration (NASA) and the NSF, is now in its 20th year. GLOBE connects students, teachers, scientists, and citizens from around the world to conduct scientific investigations about their local environment. GLOBE students take part in grade-level, interdisciplinary activities and investigations relating to the atmosphere, biosphere, hydrosphere, and soil. A multi-method evaluation of GLOBE conducted by SRI International (Butler and MacGregor, 2003) found that when trained teachers implemented the project, students were more aware of environmental issues and were able to use scientific data in decision-making. Teachers in the program reported an increase in students' technological, observational, measurement, and collaborative group skills, as well as learning new environmental science concepts. Student assessments revealed that GLOBE students scored higher in their knowledge of sampling, measurement, and data interpretation than students who had not been exposed to GLOBE. Perhaps more important, GLOBE students tended to make more science-based inferences about the natural world than non-GLOBE students. The evaluation underscored not only the need for proper training by teachers but also the importance of having students personally involved in taking repeated measurements and analyzing and interpreting data.

Another Curriculum-based project that has received evaluation is Project WINGS, a 3-year citizen science project developed by the Florida Museum of Natural History to involve youth in collecting butterfly data. In this case, the evaluators concluded that

> while WINGS appeared to be successful in connecting its participants with the natural world … it did not fully achieve its 'real world science' goal … Youth did not perceive this program strongly as science-based, but rather as an opportunity to do cool stuff outdoors with their friends. However, most youth in WINGS (62%) did report that participation increased their interest in science, and many reported that it helped them to think more positively about science. (Koke et al., 2007)

Given the focus on the educational goals of Curriculum-based projects, and the fact that they typically involve teachers or other educators, these seem well suited for developing PUS content and process. The projects may be especially useful for engaging students who do not have a pre-existing interest in science prior to participation. However, curriculum-based citizen science projects that take place in classrooms typically do not yield the community-development and personal-empowerment outcomes that have the power to impact social change (Calabrese Barton, 2012). Also, to be truly effective, curriculum projects must provide significant support and training for teachers, particularly if the projects emphasize inquiry-based learning. Furthermore, many teachers won't or can't adopt projects that are not aligned to state and/or national standards.

Community Science

The fourth and final category of citizen science that we will discuss in this review places local or regional issues at the heart of the research. Often called "Community Science" and aligned with the "Co-created" project type in the Bonney et al. (2009) typology, projects in this category usually involve data collection but typically seek to affect policy or local decision-making for public health or conservation. Community Science projects often are developed by members of the public who reach out to scientists for assistance. They may involve workshops for community members focused not only on data collection but also on how to speak to the media and public officials about scientific findings; how to use findings to influence land, air, and water quality regulations and enforcement; and how to ask answerable research questions. Bonney et al. (2009) and Shirk et al. (2012) suggest that among citizen science projects, Co-Created projects—which Community Science projects tend to be—may have the greatest potential to achieve a wide range of public understanding impacts. This is primarily because such projects typically involve participants not only in collecting data but also in developing research questions and designing research protocols, interpreting data, and disseminating results. Also, many Community Science projects intertwine engagement in the science process with the goals of public engagement in governance and science-based decision-making in ways that Irwin (1995) envisioned two decades ago.

Evidence is growing for the tremendous value of such projects for shaping policy and resource management. For example, the West Oakland Environmental Indicators Project in Oakland, California, mobilized people living in one of the city's poorest African American and Latino neighborhoods to collect air quality and health impacts data documenting the degree to which air pollution affects area residents. One outcome has been a series of recommendations that prevent short-haul truckers from idling while waiting for port pick-ups (West Oakland Environmental Indicators Project, 2013). In another project, members of the Golden Gate Audubon went from pulling weeds to collecting data on Caspian Terns to presenting their findings to local agencies. By deciding that scientific investigation offered a crucial method for addressing local conservation goals, members formed committees to recommend and implement additional monitoring projects for their chapter (Wheeden, 2012).

Such projects can influence PUS process. For instance, the Salal Harvest Sustainability Study involved 35 adult salal (*Gaultheria shallon*) harvesters in research to examine the effects of harvest intensity on commercial production in Olympic Peninsula, Washington. They worked directly with an ecologist to design and carry out the study (Ballard and Belsky, 2010). Harvesters developed a better understanding of the process of scientific investigation in terms of data reliability, validity, and methodological consistency. They increased their ability to collect field data, to record and observe consistently, and to use measurement instruments. Individuals who participated in a results interpretation workshop also gained skills in reading and interpreting graphs, drawing conclusions from evidence, and explaining how the results compared to their own observations in the forest.

Likewise, members of the Shermans Creek Conservation Association (SCCA) in southwestern Pennsylvania partnered with scientists at a local university to design and conduct a water quality monitoring study for their region. As a result, they developed an understanding about scientific methodology along with data collection skills. By participating in study design workshops, they translated their own questions into research projects, and they learned what kinds of questions can be answered through scientific investigation and what kinds of questions are better answered by other means. Study design workshops also increased participant awareness of the need to clearly articulate the intended use of data before data collection methods are chosen and have helped SCCA volunteers to redesign studies (Wilderman, 2005).

The Concerned Citizens of Tillery (CCT) and academic researchers at the University of North Carolina, Chapel Hill School of Public Health conducted a project examining Community Health Effects of Industrial Hog Operations (CHEIHO) from 2003 to 2005. CHEIHO was an epidemiological study of the acute human health effects of pollution caused by industrial hog operations near residences (Wing et al., 2008). Core members of the CCT helped design and conduct the research in partnership with the university researchers, and members of the broader public volunteered and were trained to collect data on their own family's health variables as well as to record data from air quality monitoring equipment. At the individual participant level, project personnel saw an increase in participants' awareness, knowledge, and understanding of human health and air quality issues as well as in their understanding of data collection methodologies. Furthermore, researchers reported that members of the broader community became much more aware of environmental health problems and solutions in the area. Through the project, community members gained organizing and communication skills to take action in local and state policy and decision-making to address environmental injustices in their area. Evidence that community members gained an understanding of how to use science to investigate a question and to inform policy is shown by an ordinance created to regulate the corporate hog industry statewide (Farquhar and Wing, 2003).

These examples demonstrate how community science can provide opportunities for people who often do not have a voice in environmental decision-making to use science to document otherwise hidden or contentious environmental problems. So, at least in some cases, Community Science projects may contribute positively to social well-being by influencing the research and monitoring questions that inform policy and enforcement and by expanding the use of local knowledge and experience in answering those questions. However, careful evaluation of community-level outcomes of citizen science is sorely needed (Jordan et al., 2012).

3. Where does the field go from here?

One conclusion from our review of the effectiveness of citizen science in achieving PUS is that for much of the field, the promise is presently greater than the reality. For projects looking to expand their influence in this area, effort and resources in four main categories will be required: (1) project design; (2) outcomes measurement; (3) engagement of new audiences; and (4) new directions for research.

Project design

While many citizen science projects have goals or expectations to improve PUS, few projects are actually designed to achieve public understanding outcomes. Community Science projects often achieve such outcomes by involving participants in many stages of the scientific process, and Curriculum-based projects can achieve a variety of learning outcomes by explicitly supporting or providing opportunities for the practices of scientific inquiry to develop. However, a large percentage of citizen science projects are specifically designed to increase scientific knowledge—for example, to help a land-management agency understand changing distributions of plants or animals—or to influence policy, for example, by collecting data about variables such as air or water pollution that are brought to the attention of regulatory agencies. Because most projects do provide participants with guidance in project procedures—such as reading materials or instructional videos to ensure consistency in data collection and accuracy in data analysis—project designers often assume that learning will occur and understanding will develop as participants are exposed to these materials. But practitioners who design and implement citizen science projects without specific learning objectives or lesson plans must realize that learning does not just "happen" via project participation. Citizen science participants are unlikely to change their perspectives about science unless their participation includes reflection about their role and how it relates to the processes of science.

For example, the developers of a project called the Chicago Area Pollinator Study note that

> we could have moved from education to engagement by not just delivering factual content about bees, but by engaging participants more fully in the research process … We now realize that with all the work we were doing to set up the program and its assessment, we did not spend enough time formulating and implementing a plan by which our citizen scientists would actually achieve [our] goals. (Druschke and Seltzer, 2012)

Likewise, Brossard et al. (2005) noted that TBN contained little information explicitly aimed at describing or explaining the process of science or asking participants to reflect on how their activities fit into that process.

Therefore, a significant amount of professional development support in designing citizen science projects to facilitate learning, reflection, and efficacy about the process of science and participants' role in it is necessary for citizen science projects to play a significant role in PUS.

Measuring outcomes

One reason that articulating outcomes of citizen science is challenging is the current lack of capacity for evaluation within the citizen science field (Jordan et al., 2012; Phillips et al., 2012). As the citizen science field grows and matures, improved strategies for evaluation coupled with ecologically valid assessment tools will make it easier for practitioners to design projects for maximum effectiveness and to measure whether objectives in learning and understanding are being achieved.

One effort to build evaluation capacity for citizen science through development of valid and reliable assessment tools is DEVISE (Developing, Validating, and Implementing Situated Evaluation Instruments), a project headquartered at the Lab of Ornithology and funded by the NSF (DRL-1010744). Lab researchers and a large team of colleagues have worked for several years to define desired learning outcomes for citizen science participants, to create assessment tools to measure these outcomes, and to develop online support to use the tools. Extensive interviews and surveys with citizen science practitioners have identified the following constructs as achievable and measurable citizen science project outcomes:

- Interest in science and nature;
- Self-efficacy for science and environmental action;
- Motivation for science and environmental action;
- Skills of science inquiry;
- Data interpretation skills;
- Knowledge of the nature of science;
- Environmental stewardship.

Tools to measure attainment of these constructs were released to the citizen science and informal science education communities in 2014; therefore, few citizen science projects have used them to evaluate outcomes. As the tools become more widely used, the field will begin to amass evidence of outcomes across diverse projects. Further investment allowing for automated tracking of results of these and similar tools will enhance the ability to compare outcomes across projects and to understand the overall impacts of citizen science participation.

Another product of this effort is a *User's Guide for Measuring Learning Outcomes in Citizen Science* (Phillips et al., 2014b), which provides step-by-step guidance on how to plan, implement, and disseminate evaluations. Both the DEVISE tools and User's Guide are available at citizenscience.org/evaluation.

While the short, easy-to-use instruments created through DEVISE are an important first step toward building evaluation capacity, research to develop more sophisticated measures is needed. For example, work to create assessments that are seamlessly embedded into the practice of citizen science is also under way (Becker-Klein et al., in press). Observational tools that more accurately measure data collection skills are also critically needed. Perhaps most important, strategies to measure complex aspects of science–society relationships such as trust, empowerment, and discourse in the context of citizen science are required for projects that seek to influence current notions of PUS. Collectively, such efforts should considerably advance the field's ability to evaluate what project designs are effective, to understand what conditions influence design, and to develop further understanding of how citizen science influences PUS.

Engaging new audiences

Data Collection and Data Processing projects, which reach the largest number of participants, tend to appeal to White, highly educated, and affluent audiences (Pandya, 2012). If the field of citizen science is to truly contribute to democratizing science, then it must strive to reach a wider range of audiences and participants. Curriculum-based projects have great potential for reaching underserved and minority students because, ironically, students often have no choice but to participate if their teacher or school district chooses to adopt such projects.

In addition, Community Science projects are engaging a range of audiences that typically have not engaged with science. Such projects meet people where they are—geographically, intellectually, and in terms of values, interests, families, and jobs. Engaging participants in Community Science can result in members of the public understanding science in very different ways, with new approaches to citizen science that facilitate people taking up science for themselves and using science to live their lives in whatever ways fit their livelihoods and contexts. However, Community Science projects are often limited in scope and reach, and many community-based organizations do not realize that community science workshops and trainings are available. These challenges can be addressed by expanding the reach and resources of Community Science projects through networks that bring scientists into community-based work, along with environmental justice groups such as the Global Community Monitoring (http://www.gcmonitor.org) and the Alliance for Aquatic Resource Monitoring (ALLARM) (www.dickinson.edu/allarm), which serve as umbrella organizations that empower local citizen science efforts.

A key way that projects of all types are beginning to engage new audiences is by providing multiple project entry-points as well as multiple ways to participate at different levels of commitment. For example, natural history museums with citizen science projects can draw in participants with low-commitment activities, such as casual data collection or online transcription tasks, and offer increasingly compelling activities when appropriate. By acknowledging that people have very different interests and motivations for engaging in citizen science, projects with multiple ways to participate will reach larger and broader audiences.

Reaching new audiences requires capacity-building for the field, and one way to build capacity is to partner with institutions that serve broad audiences. The US White House Office of Science and Technology Policy is building an Open Innovation Toolkit to lead federal agencies through the process of creating avenues to leverage the work and interests of active, engaged citizens to solve government problems. Several US agencies already have begun using citizen science to bolster their data collection efforts. For example, the Environmental Protection Agency's "Air Sensor Toolbox" is a means for tracking local air pollution.

Citizen science practitioners in non-governmental organizations also are building partnerships. For example, Community Science projects can learn from larger Data Collection projects to replicate and provide tools for community groups to use their strategies across larger geographic areas, such as The Public Lab's (www.publiclab.org) current development of a toolkit for building do-it-yourself (DIY) low-cost monitoring instruments and evaluation frameworks.

Expanded research

In addition to understanding what people are learning from citizen science, we need to understand HOW people learn through participation in citizen science activities. We also need to understand the role that citizen science plays in fostering or supporting lifelong science engagement. For example, participant perspectives about the issues they are investigating, interests, feelings of empowerment and self-efficacy, and relationships with citizen science programs and people are not static but evolve and develop over time. We have very little understanding of how participation in citizen science influences an individual's perception of their role in science. To understand the influences of citizen science on participants, the field needs to employ research methods that capture the depth of participant experiences and perspectives and also can encompass the wide range of projects and activities.

For example, a new NSF-funded collaborative research project entitled "Exploring Engagement and Science Identity through Participation" (DRL-1323221) is examining the relationships between engagement in citizen science, individual learning, and how people see themselves in relation to science. This mixed-methods, longitudinal research is examining six different citizen science projects (including Data Collection and Community Science projects) using interview and survey data across projects over 3 years. Results will shed light on the ways that people actually participate in scientific research, the degree and quality of participation, and how that engagement is related to participants' science process skills and interest in and sense of self-efficacy toward science. Results of this research will help to better understand the conditions that best support meaningful and lifelong relationships with science and scientific institutions and the degree to which citizen science participants use science to address issues relevant to their own lives. Preliminary findings from this work suggest that regardless of the type of project, when participants take on roles beyond data collection, they can experience very deep interactions with science and science institutions that are relevant to their lives (Phillips et al., 2014a).

Work by the Citizen CyberLab project, a collaborative research project across the United Kingdom, France, and Switzerland, is similarly examining the impacts of Data Processing projects on the creativity and learning of participants. CyberLab researchers are tracking participants' engagement with the online activities, as well as interviewing participants about their experiences and understanding of the project (http://citizencyberlab.eu/).

4. Conclusion

This review should demonstrate that citizen science has become nearly as big a concept as science itself. What was once a novel idea—lay people engaging in the scientific enterprise—is becoming mainstream. Each coming year is likely to engage more people in scientific investigation as citizen science projects become more widespread, more accessible, more fun, and more rewarding. Citizen Science is engaging, can lead to increased understanding of science content, and sometimes leads to knowledge of the process and nature of science. Evidence also is growing for the potential of citizen science to influence the lives of project participants in profound ways.

Whether citizen science can play a role in current notions of PUS as deliberative, participatory, and important for fostering science-in-society relationships—in ways that Irwin imagined in 1995—will depend on many factors. First, achieving a deep PUS through citizen science will require a much better understanding of project design to achieve desired goals. Project developers will also need to increasingly place lay knowledge alongside scientific expertise to frame relevant questions that empower individuals to become active members of the decision-making process. In addition, both local and scientific communities will need to learn new methods of discourse and deliberation while challenging scientific institutions to expand their notions of what expert knowledge is and whose knowledge counts within the realm of science. And issues of trust, fairness, equity, and risk will need to be embedded into the dialogue as seamlessly as issues concerning volunteer recruitment, protocols, and data quality.

Finally, it is important to note that not all citizen science projects are intended to democratize science or to lead to social justice outcomes. Many projects are intentionally designed to answer important scientific questions or to meet specific educational objectives. Such projects should not be held to standards for democratization of science that they were never intended to achieve.

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Notes

1. The collection and analysis of data relating to the natural world by members of the general public, typically as part of a collaborative project with professional scientists
2. We acknowledge that these categories bear some resemblance to recent typologies of citizen science that focus on the extent to which the public participates in different parts of the scientific process (Bonney et al., 2009; Shirk et al., 2012), the degree of local participation in natural resource monitoring (Danielsen et al., 2008), the “ownership” of projects by their participants (Haklay, 2013), or project goals and uses of technology (Wiggins and Crowston, 2011).

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