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Scientific impacts and innovations of citizen science

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Highlights

- Citizen science makes distinct, novel and innovative contributions to scientific knowledge and can connect scientific research with public engagement to inform policy.
- Different scientific disciplines are advancing distinct research techniques, such as computational modelling, to draw useful insights from opportunistic datasets and technologies that support new approaches to engagement.
- New scientific knowledge can be gained when citizen science puts research in the hands of people who have insights and concerns previously not addressed by academia, NGOs or government agencies.
- Citizen science may be an optimal strategy to address policy priorities, including indicators and outcomes set by high-profile treaties such as the Convention on Biological Diversity.
- Cross-disciplinary networking can advance innovations and practices around concerns shared by all disciplines employing citizen science approaches.

Introduction

From the Ten Principles of Citizen Science (Robinson et al., this volume), we can see that pursuing scientific outcomes is an integral element of citizen science. Citizen science can make distinct, novel and innovative

contributions to scientific understandings. In doing so, citizen science opens both new opportunities and new appreciations for the ways that science can engage public insight and conduct policy-relevant research. This chapter focuses on the scientific impacts and innovations across the diverse field of citizen science. It highlights the general strengths of citizen science for data collection and processing capacity, public engagement and policy, then looks to scientific innovations emerging (or in some cases being rediscovered) from different disciplinary domains.

Although the history of citizen science often focuses on environmental sciences, a rich tradition of similar research approaches is found in disciplines as varied as astronomy, meteorology and public health. Citizen science is also rapidly expanding across research domains both within and beyond the sciences, as a collaborative approach to knowledge building (see also Mahr et al. in this volume). As the field of citizen science grows, its use continues to advance discovery, foster innovation and expand the boundaries of knowledge, which can in turn reveal new ways to connect research and public engagement for policy relevance, especially when taking the opportunity to explore and connect advancements across different disciplines.

Citizen science as a distinct means of research

Citizen science depends upon the thoughtful and meaningful engagement of the public in scientific investigations. At its core, citizen science draws upon the strengths of scientific traditions, employing systematic observations and/or enquiries to produce information that can be confirmed by others. What sets citizen science apart from other research approaches is that it rejects the notion that only credentialed and/or paid scientists can take part in, lead or shape how questions are asked, data are collected, results are interpreted or findings are used (see also Haklay in this volume; Novak in this volume for more on participatory approaches). In doing so, citizen science opens up research to public input and insights, and through the combination of engagement and rigorous research, it can broaden opportunities to inform and influence policy (Vann-Sander, Clifton & Harvey 2016).

Scientific significance: Public engagement has enabled the expansion of data collection and data processing capacities (see Wyler & Haklay in this volume). In a 2016 article on the game-changing nature of internet-

enabled citizen science, Watson and Floridi describe how citizen science projects can be designed to enhance the 'reliability, scalability, and connectivity' of information. By engaging tens, thousands, and even millions of participants, citizen science can offer both human and statistical power. With observers available around the clock and around the globe, citizen science can yield observations at unprecedented temporal and geographic scales and can produce data of sufficient quality for research (Kosmala et al. 2016; and see also Williams et al. in this volume) and for evidence-based decision-making (McKinley et al. 2017). Paired with powerful and novel computational and modelling techniques, this research approach can generate useful insights even when a dataset has known limitations, such as gaps in reporting times or species that are challenging to detect (Kelling et al. 2015).

While Watson and Floridi point to the role that technology plays in these enhancements, citizen science can be a powerful strategy for distributed collaboration without technology and also at much smaller scales (see also Peltola & Arpin in this volume; Danielsen et al. in this volume). Mobilising a committed corps of 20 volunteers in a watershed, for example, can vastly enhance the capacity for local monitoring to capture and document events of concern or to have confidence in the stability of a system. What is critical in research at every scale is not to have the most data, nor even the most precise data, but to have data of known quality and data that are fit to purpose (Ellett & Mayio 1990, 23; Vaughan et al. 2003).

The practice of citizen science has also brought new technologies, new data analysis techniques and new questions. Citizen science can make historic data available for analysis (e.g., Miller-Rushing & Primack 2008; Ellwood et al. 2016) and can lead to combined datasets accessible for wider use (Schmucki et al. 2016; see also Williams et al. in this volume). Perhaps most importantly, citizen science puts science in the hands of people who have insights and concerns previously not addressed by academia or agencies (Ottinger 2016). Citizen science thus provides avenues for interrogating topics that have both scientific and social relevance – a prime nexus for informing policy (McKinley et al. 2017), whether for the environment, health, public safety or any of an increasing number of topics.

Public engagement: Scientific advancements through citizen science have only been possible because of a willingness to think differently about who is involved in the research process, how those participants engage and

what they bring to the research endeavour. Beyond engaging the public in the process of data collection, citizen science opens doors to broader knowledge exchange about the research in question (McKinley, Briggs & Bartuska 2013). Listening to participants' experiences can increase scientists' and policymakers' awareness of social concerns and influencing factors. This can be particularly important in complex settings such as conservation and medicine, where findings and implementations may be context-specific and where generalised, 'objective' knowledge may be less useful than scientific traditions generally assume. Research in all areas of exploration indicates that the more deeply participants are involved in the process of investigation – from shaping the research question to interpreting and acting on the results – the more profound the outcomes are for participant learning and for policy action (Danielsen, Burgess & Balmford 2005; Shirk et al. 2012; Stepenuck & Green 2015; and see Nascimento et al. and Smallman, both in this volume). Regardless of the depth of engagement, a significant motivator for many who choose to participate is an understanding that they are making a contribution, whether to broadening scientific understandings or to making a change in the world (Raddick et al. 2013; Alender 2015; Tsueng et al. 2016).

Policy: In an ideal world, policy decisions would be informed by evidence, but actionable evidence may not always be available, especially in cases calling for rapid or anticipatory responses (e.g., disasters, emerging diseases) or in complex systems (e.g., climate impacts, fisheries) (see, for example, Bower et al. 2017). Policy decisions are thus often made without evidence or with data not fit for purpose, and therefore against a background of uncertainty. Citizen science mobilises multiple observers and therefore has the potential to fill data gaps (Chandler et al. 2017) and to procure data in a timely manner (Vaughan et al. 2003). Careful design is required to ensure that the data collected are of appropriate and known quality for the purpose at hand (Shirk et al. 2012; Danielsen et al., 'A Multicountry Assessment', 2014; Kosmala et al. 2016). Citizen science research can also be targeted towards questions informed by policy needs or stakeholder concerns to yield the most relevant data (McKinley, Briggs & Bartuska 2013). Participants in such research, where stakes are high, have every incentive to ensure their data are defensible (Ottinger 2016). With all of these factors in mind, Danielsen et al., 'Linking Public Participation', (2014) suggest that citizen science may be an optimal strategy to address policy priorities, including indicators and outcomes set by high-profile treaties such as the Convention on Biological Diversity.

Citizen science innovations across disciplines

It is possible to see – and learn from – advancements in research impacts and innovations emerging in the different scientific disciplines where citizen science is employed. This section briefly looks at three different research domains – geophysical, biomedical and social science – to explore the scientific contributions of citizen science and the innovations that have enabled those outcomes. In doing so, it points to advances in public engagement and policy that can also be seen in these areas. It does not aspire to provide a comprehensive review, but rather to offer a glimpse into the practices and impacts in different disciplines, which may help expand thinking in the larger field.

Geophysical/Geospatial: Earth systems and earth observation research are yielding scientific advances through citizen science at both global and local scales, and advancing this work in part through innovative uses of remote sensing, social media and distributed sensors. An entire special issue of the journal *Remote Sensing* (Fritz & Fonte 2016) is devoted to sharing outcomes of citizen science including research into land cover (Laso Bayas et al. 2016), forest biomass (Molinier et al. 2016), water clarity (Busch et al. 2016) and the timing of lifecycle events (e.g., Elmore, Stylinski & Pradhan 2016) among other topics. Seismologists have refined methods to harvest streams of Tweets to improve real-time research into earthquake intensity (D'Auria & Convertito 2016) and range of perceptibility (Earle, Bowden & Guy 2012). Hydrologists have turned to social media as well, capturing photographs of flood events to estimate flow rate and depth (Le Coz et al. 2016). Geophysical scientists are also working in person with concerned communities to assess and monitor pollutants in soils and garden vegetables (Ramirez-Andreotta et al. 2013), air pollutants near gas drilling sites (Macey et al. 2014) and changes in water quantity and quality (Stepenuck & Green 2015).

These approaches to research can facilitate both rapid and collaborative policy responses to environmental change (Minson et al. 2015; Stepenuck & Green 2015). To this end, work in this domain is confronting and advancing procedures and measures that relate to issues of public engagement, such as around risk (Ramirez-Andreotta et al. 2013) and power and participation (Ramirez-Andreotta et al. 2015; Stepenuck & Green 2015).

Biomedical: In their systematic review of crowdsourced research in medical fields, Ranard et al. (2014) found papers in hematology, radiology, genomics, molecular biology and more, which describe citizen science strategies including problem-solving and the distributed surveillance of symptoms or treatment options. Innovations in online platforms for problem-solving, such as FoldIt and Zooniverse, have engaged communities of gamers-turned-analysts to advance cancer research, protein mapping, DNA sequencing and neurobiology (Kawrykow et al. 2012; Peplow 2016). What Ranard et al. label 'surveillance systems' include strategies designed to elicit patient-contributed datasets, whether through project-specific portals or social media channels, which are sufficient to explore trends in such areas as disease outbreak (Smolinski et al. 2015), drug reactions (Salathé 2016) and risk factors for disease transmission (Garcia-Martí et al. 2016). Technologies developed for the Mark2Cure project, for example, engage volunteers in mining peer-reviewed journals to identify, annotate and curate relevant papers out of a broad literature with overlapping acronyms (Tsueng et al. 2016). Innovations are not all technological – community-based participatory research (CBPR), although far from new, continues to demonstrate the significance of collaborative learning where patients, patient advocates, health workers or at-risk communities help define research goals and processes (Wallerstein & Duran 2006). Innovations in CBPR include exploring opportunities for collaborative research to organise and mobilise concerned communities to take action around their health concerns (Cohen et al. 2016), and opening up avenues for qualitative methodologies in collaborative health research (Clark & Ventres 2016).

Policy implications in this domain may most easily be seen in CBPR work, where partnerships can help confront inequities in biomedical research and services (Israel et al. 2001) and are at times even specifically driven and directed by policy concerns (Themba & Minkler 2003). The fine line between researcher and subject in citizen science in the biomedical sphere has led to an extensive conversation around research ethics (del Savio, Buyx & Prainsack 2015; Kolman 2016; Vayena & Tasioulas 2016; Woolley et al. 2016). Work in this discipline has also helped confront and advance thinking on issues including privacy (Del Savio, Buyx & Prainsack 2015); patients' rights (Woolley et al. 2016); and even the concept of patient/public 'right to science' (Vayena & Tasioulas 2016).

Social science/humanities: Although it may be less common to think of social science and humanities research in relationship to citizen science, many of the same techniques are being employed and advanced

to understand archaeology, literature, history and social dynamics. In a review of crowdsourced digital humanities research, Terras (2016) describes ways in which text and image analysis, transcription and annotation are helping to research, archive and make publicly available aspects of cultural heritage that might otherwise remain locked in museum basements or lost to time (as in the case of events and ephemeral art). Archaeologist Parcak (2015) highlights the opportunities for technology – specifically remote sensing – to document geopolitical events and conduct social and behavioural research via public access to satellite images and open mapping platforms. She is pioneering the use of aerial imagery to engage the public in identifying promising sites for archaeological exploration (Gewin 2016). Satellite observations can also facilitate monitoring and research of social conflict, human rights violations and the extent and impact of environmental disasters (Zastrow 2014; Notley & Webb-Gannon 2016). Innovative technology use is also enabling human-centred research, including studies of geographic trends of sexual behaviour (Davis et al. 2016) and correlating patterns of physical exercise with barriers to accessing outdoor spaces (Rosas et al. 2016).

Some projects and platforms in this domain are designed to have clear short- or long-term policy implications, such as to facilitate dialogue and transparency (Terras 2016) or direct action and advocacy (Rosas et al. 2016). Technology can improve understanding and management of issues of privacy (Davis et al. 2016), and can also raise concerns about equity in social research (Notley & Webb-Gannon 2016). Work with direct social implications reminds us that 'the crowd' (which includes scientists, per Parcak 2015) has interests and a stake in outcomes, and therefore scholars in this domain are working to deepen understandings of how politics and objectivity are approached in relation to research and public engagement (Notley & Webb-Gannon 2016).

Transferring innovations to advance work across disciplines

The development of citizen science in diverse disciplinary contexts has implications for the larger field. While some insights and innovations are disciplinary-, context- or project-specific, many may be transferrable to other settings. Opportunities are plentiful for advancing work by transferring innovations, and examples can be seen in terms of technology, computational strategies, engagement approaches and the practice of

research itself (for the practical implications, see also Williams et al. in this volume).

Technology transfer: The rapid diversification of projects on the Zooniverse platform is a primary example of technology transfer. This platform for digital image classification, designed for public processing of astronomical images, is now employed for marine science, climatology, cancer research and more (see, for example, Tinati et al. 2015). Terras (2015) points to Zooniverse as a model platform for technologies developed to enable cultural heritage research. Hardware technologies are also transferable. Sensors in smartphones, smart watches and elsewhere allow data to be captured and shared in almost any setting (for example, a phone camera can document both species sightings and cosmic ray strikes) – a 2016 *Nature* article by Cartwright offers cross-cutting advice for scientists in any discipline who are looking to leverage these tools. Where hardware tools are not available or accessible, participants have built them – tools developed by do-it-yourself community scientists to enable community-based monitoring are now being adopted by professional researchers because of their quality and affordability (Dosemagen 2017, personal communication; and see also Volten et al. in this volume). The US Forest Service also notes that public engagement in research helps with technology transfer to private landowners/resource managers otherwise left behind as the industry rapidly advances (McKinley, Briggs & Bartuska 2013).

New computational approaches: The complexity of many citizen science datasets has led to innovative applications of data analysis techniques that have utility far beyond the discipline in which they were developed. Hochachka et al. (2012) describe the early application of sophisticated 'big data' statistical analysis and modelling techniques to citizen science in ornithology, and outline the development of new, 'semi-parametric' techniques that have particular utility for any citizen science analyses where limited assumptions can be made about individual data points. Algorithms developed for analysis of data from the Zooniverse platform provide avenues for reaching consensus on image classification within large datasets, based on the consistency of a user's contributions – where choices are binary, consistent annotations are useful regardless of whether they are consistently right or consistently wrong (Shamir, Diamond & Wallin 2016). Other transferable citizen science techniques include advances in machine learning that help identify and remove data 'noise' caused by glitches (Zevin et al. 2017), improvements in pattern recognition to auto-

mate photo identification of species (Andrzejaczek et al. 2016), and new developments in protocols that enable the repurposing of volunteered geographic information if it has been collected as vector data (Mooney et al. 2016). Bridging data analysis and policy, decision support tools have also been developed to help make sense of complex data in direct relationship to policy needs and priorities (Sullivan et al. 2009).

Opening engagement: Innovative projects continue to engage the public in new ways and in new aspects of research, which can create or enhance engagement opportunities in other disciplines. Research by Tinati et al. (2015) across the Zooniverse platform suggests that the same basic engagement strategies are applicable across the platform, regardless of research discipline; in addition, they suggest that their most valuable insights and advances came from recognising and enabling the work of volunteers as peers in conducting investigations. The FoldIt project revealed the value of inviting non-scientists to assist with scientific problem-solving. In one of the first major publications to document the success of this platform for collaboratively intuiting the structure of protein molecules, the authors (including both project leaders and solvers; Khatib et al. 2011) suggest that similar online game strategies can engage people in solving other complex problems (see also Novak et al. in this volume). Non-scientists are assisting with literature searches (Tsueng et al. 2016), developing scientific tools and instrumentation (e.g., Ottinger 2016) and participating in statistical analyses (Alliance for Aquatic Resource Monitoring 2010), most of which represent new frontiers for engagement which could be relevant to any research area. More directly connected to policy prospects, Tucker et al. (2016) present a method of 'speed dating' to match academic researchers and community leaders according to common interests and to develop collaborative research proposals. Whether the research topic is earthquakes or human rights violations, projects are also advancing response times and refining mechanisms, not just to collect data, but also to provide data tailored to inform decisions (e.g., Notley & Webb-Gannon 2016).

Implications for the practice of science itself: The collaborative nature of citizen science invites new considerations about how science is accomplished and what kinds of practices make science effective (Wyler & Haklay in this volume). Some originally disruptive aspects of citizen science have begun to shape the broader scientific landscape. For example, Franzoni and Sauermann (2014) suggest that the unconventional willingness of what they call 'crowd science' initiatives to publish intermediate results

may speed innovations, in contrast to traditional research where findings are published only as a culmination of research efforts. Citizen science projects have also helped to bolster movements in open data and open-access publishing. In any domain, citizen science is helping to advance how to define, facilitate and document quality across science done by anyone, reminding all researchers of the responsibility to not take data quality for granted (Newman, Roetman & Vogel 2015). Citizen science can also offer a means for pursuing integrated research such as investigations of coupled human/natural systems (Crain, Cooper & Dickinson 2014), for example cases where livelihoods and natural resources are interdependent. Finally, where policy outcomes are an impetus for public engagement, citizen science can help focus research efforts towards garnering knowledge that provides a basis for specific actions (McKinley et al. 2017), such as whether or not to implement a treatment for the problem at hand.

Conclusion: Implications for citizen science as a field of practice

Looking at advances within distinct research disciplines, and their transferability to other contexts, shows how opportunities for cross-disciplinary networking can enhance the practice and appreciation of citizen science more broadly. Citizen science is necessarily disruptive, and is already changing how science takes shape both within scientific institutions and in communities. An inclusive community of practice, spanning diverse disciplines and definitions, can facilitate both a more rapid uptake and adaptation of relevant technologies, and bring research approaches to new purposes. Cross-disciplinary networking can also help advance practice regarding concerns shared across all disciplines, such as issues of ethics, democratisation, participation and policy (e.g., Silka 2013). The Ten Principles of Citizen Science call out these and other ideas that are broadly applicable, no matter the citizen science setting (Robertson et al. in this volume).

Cross-disciplinary work can also aid citizen science by demonstrating the broad *social* and *scientific* significance and relevance of public engagement. Citizen science research within any disciplinary domain is well-served when it can leverage past successes to have the greatest impact, in ways that elevate the robustness of the research, the opportunities for meaningful public engagement and the relevance for policy. It is also critical for the field of citizen science as a whole to reveal and promote exemplar cases from all disciplines. This will help all stake-

holders (including scientific peers who do not themselves use citizen science) understand and appreciate the value of citizen science as well as the investments necessary – in science, engagement and policy applications – to ensure its success. Connecting across disciplines offers the opportunity to draw strength from others' successes as well as lessons from their innovations, and from how they creatively advance science in relation to public interests and policy concerns.

Parcak (2015) points out that scientists increasingly want to see their research make a change in the world. The utility of citizen science for policy-making may depend, according to Vann-Sander, Clifton and Harvey (2016), on moving beyond a 'science-centric' view of citizen science. This recommendation must not be mistaken as being about moving *away* from the science in citizen science, as this may risk abandoning the rigour of scientific practices and outcomes (whether those practices involve monitoring, analysis, tool-building or cataloguing) that inform policy and even the motivation driving and serving public participation. Rather, Vann-Sander, Clifton and Harvey allude to an opening up and broadening of science to include attentiveness to the multiple interests and relationships that converge through citizen science, and which are necessary to engage in effecting policy change.

Just as with the practice of science more generally, citizen science has a unique character in each different discipline, but in all disciplines, citizen science initiatives demonstrate a shared, fundamental appreciation for the process of observation and inquiry in pursuit of verifiable knowledge gains. Citizen science helps expand the pool of collaborators and knowledge contributors who engage in this process, and in doing so, can engage broader public insights and concerns, inform the policy process with more complete and relevant datasets, and bring the process of knowledge generation more closely into conversation with the policy process and issues relevant to that process. At its best, science, policy considerations and public engagement are mutually reinforcing in policy-relevant citizen science. Divorcing the science from citizen science would be a disservice to the commitments and expectations of contributors, diminish its significance for policy and limit the ways that science and citizens intersect to inform new approaches to research. It is possible to imagine a future that moves *beyond* the 'science-centric' view of citizen science in ways that maintain the integrity and utility of the science at the heart of citizen science, in service to policy and an engaged public.