Citizen Science: Potential New Opportunity for Consent-Based Siting Processes – 16608

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ABSTRACT

Citizen science is a global phenomenon, as millions of volunteers are collecting, analyzing, and sharing data that contribute to scientific knowledge. Recognizing its potential, the U.S. 2013 Open Government National Action Plan encouraged Federal agencies to harness American ingenuity toward helping address a broad range of scientific and societal challenges, specifically invoking crowdsourcing and citizen science. The October 2015 Plan reinforced this charge, calling on agencies to increase public participation through both means. Thus, citizen science opportunities are actively being sought across a wide range of Federal programs. Meanwhile, all nations with commercial nuclear reactors face the challenge of managing the spent nuclear fuel and high-level radioactive waste produced. Consent-based siting of facilities to manage these materials is considered an essential aspect of this shared challenge. A variety of other agency programs have illustrated the role citizens can play in strengthening engagement, empowerment, and scientific research. With these same themes important to planning for nuclear waste management, citizen science could represent a potential new opportunity for this national effort. Online resources were investigated to understand the nature and range of citizen science projects and seek insights for possible new applications. Results show that volunteers are contributing to research in areas from archeology to zoology, and extending from the ocean floor to outer space. A large number of the collaborations involve characterizing local environmental conditions and monitoring changes over time. This paper highlights insights from several projects that illustrate the contributions citizen scientists can make to advance scientific knowledge and assist national and international programs.

INTRODUCTION

Citizen science is broadly described as public participation in research to increase scientific knowledge, often in collaboration with professional scientists and scientific institutions. Its popularity has markedly increased during the last decade as enabled by the Internet and other technology advances. This paper explores the potential for citizen science to represent a new opportunity for consent-based siting processes for facilities needed to manage spent nuclear fuel (SNF) and high-level radioactive waste (HLW) from commercial power plants. To set the stage for this exploration, background information is first provided on the Open Government Partnership, the regulatory framework for public involvement in planning for nuclear waste management facilities, and the U.S. Department of Energy (DOE)'s consent-based siting initiative. The approach for learning more about citizen science is then briefly outlined, followed by results that describe what citizen science is, how it has been applied, and some of the benefits and challenges. Also provided are insights regarding the potential opportunity of citizen science for consent-based siting processes. It must be recognized that a consent-based siting process has not yet been developed for the facilities needed to manage SNF and HLW from commercial reactors in the United States, as DOE is currently seeking inputs to design such a process. Given that the process will not be defined or implemented for some time, this early exploration and the example citizen science activities noted herein should not be viewed as indicating a path forward in any way; instead, these examples simply illustrate the potential opportunity citizen science might offer in the future as the process unfolds. That is, this paper should not be misinterpreted as suggesting that citizen science be applied to consent-based siting of nuclear waste management facilities. Rather, the intent is to introduce the concept into the discussion as efforts get under way to define a fair and effective consent-based siting process.

Open Government Partnership

Spurred by advances in information and communications technology (ICT), in 2011 the United States joined with seven other countries (Brazil, Indonesia, Mexico, Norway, Philippines, South Africa, and the United Kingdom [UK]) to establish the Open Government Partnership (OGP). The OGP objective is to provide an international platform for government and civil society to work together toward making governments more open, accountable, and responsive to their citizens. Key aims include promoting transparency, empowering citizens, and harnessing new technologies to strengthen governance [1]. Each nation is responsible for developing a country action plan on a regular cycle as a condition of membership. The United States has prepared three OGP National Action Plans. The first was released in September 2011 and established a national commitment to expand public participation in government, toward the open exchange of information and perspectives [2]. In December 2013, the second plan extended beyond this broad commitment and called on Federal agencies to harness American ingenuity to help address a wide range of scientific and societal challenges, specifically invoking crowdsourcing and citizen science [3]. In October 2015, the third plan further emphasized this point, with access to information being one of several key themes. Within this theme, "advancing open science through increased public access to data, research, and technologies" is described as including interagency dialogue to identify best practices for how to foster the development of low-cost instrumentation and work with stakeholders to get these instruments into the hands of volunteers so they can help advance scientific and societal goals [4].

The 2015 National Action Plan also includes a primary commitment to "raise the voice of citizens through improved public participation in government," and a further commitment to engage the public on our greatest national challenges [4]. This plan describes the importance of an informed and active citizenry representing all sectors, and facilitating new avenues to help leverage fresh perspectives and empower communities to help solve problems. Like the previous plan, this one also specifically calls out citizen science and crowdsourcing. In addition to helping facilitate and coordinate open innovation opportunities across the government, the plan also commits Federal agencies to cataloging their current open innovation activities including citizen science and crowdsourcing activities, and it directs the General Services Administration to create a new project database of citizen science and crowdsourcing projects. That effort is already under way.

Meanwhile, the OGP has increased nearly nine-fold in four years. By the end of 2015, 70 countries were involved, most as formal participants; a handful (including Australia) are in the process of developing action plans that will formalize their participation [1]. Member countries extend from North and Central America and much of South America to New Zealand, the United Kingdom and most of Europe, and a number of countries across the Middle East, Asia, and Africa. (Russia was a member but withdrew in 2013.) Achievements reported from the 2015 OGP Global Summit in late October included progress on global goals as well as plans for implementing open government on a local level [5]. Upcoming pilot applications might offer insights for future citizen science initiatives in other programs emphasizing local involvement (such as related to participatory planning for waste management). The key point of the U.S. OGP National Action Plans is that Federal agencies are committed to pursuing citizen science activities, with a particular emphasis on engaging the public to help address national challenges. Given this emphasis, a consent-based siting process for nuclear waste management facilities could be considered to represent a potential opportunity area.

Regulatory Context for Public Involvement in Planning for Nuclear Waste Management

Managing the SNF and HLW produced from generating electricity in commercial reactors is a national responsibility. The DOE is seeking input from states, communities, Tribal Nations, and interested stakeholders to guide the development of a fair and effective process for siting facilities needed to manage these materials. Overall planning will also involve formal mechanisms for public involvement outlined in existing Federal laws and regulations. One such formal mechanism is the preparation of analyses pursuant to the National Environmental Policy Act (NEPA) of potential environmental impacts associated with a federal agency proposal to address the management of SNF and HLW. Pursuant to NEPA and its implementing regulations, a federal agency is required to consider the potential environmental consequences of the proposed Federal action and its reasonable alternatives and, in many cases, involve the public in that process. Where an agency prepares an environmental impact statement, the public provides comments during the scoping phase of a proposed action and on the draft environmental impact statement.

Other regulations outline requirements for public participation related to the licensing process for nuclear waste management facilities. As an example, public involvement in the licensing of independent spent fuel storage installations (ISFSIs) at commercial reactor sites is defined in 10 Code of Federal Regulations (CFR) Part 72 (*Licensing Requirements for the Independent Storage of Spent Nuclear Fuel, High-Level Radioactive Waste, and Reactor-Related Greater Than Class C Waste*), and public involvement in the process for a geologic repository is defined in 10 CFR Part 60 (*Disposal of High-Level Radioactive Wastes In Geologic Repositories*). Under these regulations, an implementer collects data (including environmental characterization data for a candidate site), develops designs, analyzes safety, and presents the conclusions in the form of a license application to the U.S. Nuclear Regulatory Commission (NRC). There are opportunities for stakeholders and the broader public to provide input, but communication is typically one-way with no formal mechanism for citizens to provide feedback via interactive discussions with the implementer. Formal feedback is only provided through the licensing process, such as commenting on the site characterization analysis provided by the NRC, and commenting on the NEPA review document (e.g., DEIS) through public hearings held as part of the license application process.

Consent-Based Siting

In 2012, the Blue Ribbon Commission on America's Nuclear Future (BRC) released its report with eight key recommendations [7], one of which called for "[a] new, consent-based approach to siting future nuclear waste management facilities." In 2013, the DOE issued its *Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste* (hereafter Administration's *Strategy*) [8]; key statements include the following: "First, it serves as a statement of Administration policy regarding the importance of addressing the disposition of used nuclear fuel and high-level radioactive waste; it lays out the overall design of a system to address that issue; and it outlines the reforms needed to implement such a system. Second, it presents the Administration's response to the final report and recommendations made by the *Blue Ribbon Commission on America's Nuclear Future* ('BRC')." Also, "[t]he Administration's *Strategy* endorses the key principles that underpin the BRC's recommendations." In addition, "[t]his Strategy includes a phased, adaptive, and consent-based approach to siting and implementing a comprehensive management and disposal system." Neither the BRC nor the Administration's *Strategy* describe what a consent-based siting process is. As stated in the Administration's *Strategy* [8]: "Critical elements for successful implementation of this Strategy include the establishment of a consent-based siting process...." This concept is reflected in DOE's recent initiative, as highlighted below.

In December 2015, DOE launched its consent-based siting effort, publishing an Invitation for Public Comment in the Federal Register to solicit input on important considerations in designing a fair and effective process for siting the facilities needed to manage our nation's spent nuclear fuel and high-level radioactive waste. The Department held a kickoff meeting in January 2016 to discuss planning activities for an integrated waste management system and a consent-based approach to siting. Upcoming public meetings were also announced, as opportunities for DOE to hear from the public, communities, states, Tribal Nations, and all interested stakeholders on what matters to Americans, as the Department moves forward in developing a consent-based process. The input provided, including through the Invitation for Public Comment and eight public meetings, will inform the design of a consent-based siting process, which will in turn serve as a framework for engaging with potential host communities in the future. Ultimately, the Department aims to work collaboratively with the public and interested communities to begin identifying potential partners in managing the nation's spent nuclear fuel and high-level radioactive waste [9,10].

The U.S. Nuclear Waste Technical Review Board (NWTRB) is among many organizations that have emphasized the role of public involvement in siting efforts, with a recent emphasis on repositories for final disposition. For example, a 2013 article describing lessons from consent-based siting approaches in the United States and eight other countries includes highlights of local community involvement [11]. Further details for these countries plus a tenth (China) are presented in the extensive November 2015 summary and analysis reports on designing a process for selecting a deep-mined geologic repository for SNF and HLW [12,13]. One of the four recommendations in the NWTRB letter transmitting these reports to Congress and the Secretary of Energy calls for a transparent and meaningful participatory process, notably for any changes to site suitability criteria during the siting process. The reports note that the technical problem of site suitability has become more of a socio-technical challenge in previous repository siting efforts by the United States, Canada, Germany, France, and Sweden. Consent-based siting is identified as the modern model, with the technical suitability or acceptability filter applied first in some cases, while in other cases the candidate sites are put through the social acceptability filter first (recognizing the influence of technical suitability information). In either case, the social context is considered essential.

Interestingly, four of the ten nations profiled in the NTWRB report are not part of the OGP, that is they have not yet signed on to this open government initiative. China is not a member, and perhaps more surprisingly, neither is Japan, Germany, or Switzerland (Canada, Finland, France, Sweden, and the UK are members, with France having joined in 2014) [1]. The OGP National Action Plans, Administration's *Strategy*, and early planning for a consent-based siting process all reflect a strong commitment to citizen participation and collaboration to address the complex national challenge. The recent NWTRB evaluation of consent-based siting processes emphasizes the same points. Because these principles are also cornerstones of citizen science, a potential opportunity is suggested for this area.

DESCRIPTION OF APPROACH

To explore the potential for citizen science to be an opportunity for consent-based siting processes, a literature search was conducted to help understand how citizen science has been characterized, how it has been applied, and what benefits and challenges have been identified. Many citizen scientists are volunteers without formal training, so much of the documentation for these projects is in a format other than traditional scientific publications. Standard literature search approaches tap peer-reviewed journal articles and technical reports accessed via established compilations such as the Web of Science. In contrast, many citizen science projects are described in mainstream media (news articles), social media (blogs), and project-specific websites. For this reason, information was also sought via Internet searches using key words such as "citizen," "civic," "participatory science," and "volunteer monitoring." These terms were also used in combination with "benefit," "opportunity," "achievement," and "result," as well as "barrier," "challenge," "issue," "limitation," and "obstacle." Finally, OGP progress reports were searched to explore whether citizen science, civic engagement, or similar concepts are discussed with regard to radioactive waste management or nuclear facilities in other countries.

DISCUSSION OF RESULTS

The online search produced hundreds of articles and websites with information relevant to citizen science. Selected highlights are summarized below to frame insights into possible future contributions.

What Is Citizen Science?

Although the term citizen science is relatively new, the practice extends as far back as the 1880s, with a survey that had lighthouse keepers counting and identifying birds that hit their lighthouses; for another survey during the same period, volunteers tracked migrating birds [14]. In 1900, the National Audubon Society began its annual Christmas bird count (with 27 people in 25 locations), and it has been held every year since [15]. Now more than a century after these projects, ICT advances have sprung participatory science from the realm of individual hobbies to that of networked mobile devices, cloud services, and the Internet of Things. Soon after the first OGP National Action Plan was released, a handful of visionary agency scientists met to establish the Federal Community of Practice on Crowdsourcing and Citizen Science (Community) [16]. Since 2012, the Community has grown to more than 200 members representing agencies across the Federal government, from the White House Office of Science and Technology Policy, U.S. Environmental Protection Agency, and 17 Departments (including DOE) to the U.S. Geological Survey, Bureau of Land Management, National Science Foundation, Peace Corps, and more. This Community describes crowdsourcing as an open call for voluntary assistance from a large group of individuals to provide information or help solve a problem; it can involve obtaining services, ideas, or content, notably from an online community. Citizen science is described as an open collaboration with the public, including to formulate research questions, collect and analyze data, interpret results, make new discoveries, develop technologies and applications, and solve complex problems. It involves mobilizing the public to participate voluntarily in the scientific process to address scientific and societal problems, including a paucity or lack of information.

Crowdsourcing for science can involve people using their computers to help review and interpret massive data sets. It can also involve people playing specialized video games that simulate systems and processes to uncover new possibilities. Examples include: scanning images of outer space for anomalies to support astronomy research, scanning satellite images of Earth for anomalies to support archaeology research, and using video games to play with protein folding configurations to support medical research. Crowdsourcing also includes citizens giving professional scientists access to their personal computers when not in use, to give them extra computing power for computations that require long run times.

Citizen science involves observing, measuring, and reporting on various aspects of our environment across a wide range of subjects. Examples include recording precipitation, invasive species, migrating birds or butterflies, ground motion sensed during an earthquake, and air and water quality. This can be considered a subset of crowdsourcing (other applications extend well beyond science); within the science arena, it could be viewed the other way around. Some people separate "civic tech" from crowdsourcing and citizen science, preferring to define it distinctly as technology that enables public engagement or participation, or as using technology (primarily information technology, such as the Web) for the public good. This paper uses civic science broadly to cover all three terms in the context of scientific and technical applications.

The rapid growth of citizen science has mirrored ICT advances, as mobile devices and the Internet are core enablers. A 2015 Pew Research Center study reports a near-doubling of smartphone ownership by U.S. adults since 2011 (from 35% to 63%), with higher percentages of 83% and 86% for adults under 50 (ages 30-49 and 18-29, respectively). Further, nearly three-quarters of U.S. adults own a laptop or desktop computer [17]. In 2013, the United Nations reported that more people had mobile phones (6 billion) than access to a toilet or outhouse (4.5 billion) [18]. ICT has reached around the world, as nearly 3.2 billion people have Internet access [19]. Investment in civic technology was reported to top $6 billion in 2015 (a small fraction of the estimated $140 billion invested in government technology) [20,21]; projected increases will likely spur further citizen science opportunities. Low-cost miniature sensors and do-it-yourself kits have facilitated citizen science, while smartphone apps and plug-in sensors have further enabled participation. Activities are usually free or involve a nominal cost for materials people don't already have (e.g., beyond a smartphone or computer with Internet access). A recent study estimates that 1.3 million citizen science volunteers across biodiversity projects alone (388) are contributing up to $2.5 billion a year in in-kind funding, more than most Federally-funded studies, and covering a larger area over a longer time [22].

How Is It Applied?

Citizen science spans a wide range of topics, from archeology to zoology, with applications extending from the ocean floor to outer space. Online compilations include over 100 federal projects in the Wilson Center Commons Lab database (https://ccsinventory.wilsoncenter.org/); nearly 180 projects in Cornell Ornithology Lab Citizen Science Central database (http://www.birds.cornell.edu/citscitoolkit); more than 200 in the Scientific American database (http://www.scientificamerican.com/citizen-science/), and more than 700 projects in the SciStarter database (http://scistarter.com/finder). Many databases are searchable by topic and location; e.g., a search of SciStarter for "tree" produces 40 projects that extend from urban forests in Harlem to the great yew hunt in the United Kingdom and landmark trees in India. In December, Scientific American identified 2015's top ten citizen science projects based on popularity [23]. Topping the list was a project led by Tufts and the University of Pennsylvania that studies how an owner's personality affects their dog's behavior, with volunteers uploading information on a website hosted by Vanderbilt University. Second is a National Aeronautics and Space Administration (NASA) study of soil moisture from space, with volunteers collecting samples from their backyards to ground truth satellite data. (Participants receive an alert when the satellite is flying overhead, go get a scoop of soil, weigh it, dry it for a day or two, then weigh it again to determine moisture content, and upload the data to the project website.) A large number of citizen science projects focus on environmental monitoring to support local, state, national, and international programs – including for air and water quality, natural resources, and biodiversity, to assist with projects ranging from resource protection to facility planning and disaster response. An example of the latter is DOE's "Lantern Live" mobile app that helps users in areas affected by disasters crowdsource information about local gas stations, power outages, and safety tips [24]. Other examples are given below.

Conservation and Climate Change

The Audubon Christmas bird count is considered the longest-running project with significant contributions to conservation research. Now conducted each year in coordination with the Cornell Lab of Ornithology, it extends across the Western Hemisphere. The 115th event drew more than 70,000 participants from the United States and Canada alone, with bird counts reported for nearly 2,500 locations. More than 68 million birds were tallied in the United States, and another 3.5 million in Canada. Together with volunteers in the Caribbean, Bermuda, Latin America, and the Pacific Islands, these citizen scientists reported a total of 2,100 species, or about 1/5 of all avian taxa on earth [15]. With observations spanning more than a century, participants have contributed to research studies ranging from conservation and avian and ecosystem assessments to climate change. Many projects involve observations about cyclic and seasonal phenomena, or phenology. The National Phenology Network (NPN) began at Montana State University in 1960 and expanded to other universities; since 2007, it has been coordinated by the University of Arizona in partnership with the U.S. Geological Survey [25]. Since its inception, thousands of volunteers have recorded seasonal changes such as timing of snowmelt and wildlife migrations, spring budbursts and blooms, and fall leaf drops. In 2012, NPN announced its impressive achievement of 1 million records [26]; the wealth of data are considered highly valuable to climate change studies. An example further contribution is suggested by the first Nature's Notebook entry of 2016, which describes reports from many citizens about bulbs sprouting, flowers blooming, and insects flying as a result of the warm December 2015 [27]. The potential additional value involves targeted reporting related to vector-borne diseases such as the Zika virus. For example, in areas of heightened concern for mosquito transmission (such as the southern United States), informal observations like this might be used to activate a citizen scientist network to begin reporting mosquito presence by location and type; the combined data could then be used to prompt alerts or other protection measures as indicated.

Weather and Water

Weather forecasting is another area that has benefited substantially from citizen scientists. Beginning in 1993, the Weather Underground literally put weather on the map with citizens contributing data from backyard weather stations to fill in large areas of the United States not covered by National Weather Service or other public stations. Data contributed by 180,000 people from their personal stations [28], has vastly improved forecasting, which benefits our collective well being given weather's influence on our personal safety and our economies as well. The volunteer Community Collaborative Rain, Hail and Snow (CoCoRaHS) Network is now the largest provider of daily precipitation observations in the nation, with nearly 7,000 reports as of early 2016. Supported by the National Science Foundation (NSF), National Oceanic and Atmospheric Administration (NOAA), and others, this grassroots organization aims to provide high-quality data to support natural resource, education, and research applications. Its interactive website includes links to training [29]. Like weather data, citizen scientists have long contributed to local, state, and national water programs, measuring the quality and flow of surface waters and the quality and depth of groundwater. Some citizen scientists have also helped install groundwater wells for environmental monitoring programs [30]. Further contributions to such programs with links to weather data might consider potentially using precipitation data from extreme events to help inform the interpretation of subsequent groundwater monitoring data (e.g., per increased recharge), or to provide location-specific context to support design basis assumptions for new facilities that might be considered in the future.

Radiation

Citizen science for radiation measurements on land and water illustrate the role technology developers (or the maker community) play. The nonprofit Safecast team helped local citizens measure radiation levels on land after the Fukushima accident, combining small Geiger counters with open-source software so data could be posted and mapped online [31]. Within three years, citizen scientists had helped generate 15 million data records. As with many technologies, the cost has dropped significantly since the first model (from $1,000 in 2011, which included a $700 commercial device connected to the customized electronics system measurements, to $200 for the current b(bento)Geigie Nano, which can be used with a mobile device). The current model was used in June 2015 for an international aero-gammaspectrometry exercise. Like most handheld detectors, the detection limit is higher than natural background levels, so it would be used after a release when levels are higher. Halfway around the world, the Woods Hole Oceanographic Institution established *How Radioactive Is Our Ocean?* to measure radioactivity in sea water following Fukushima [32]. People were asked to donate $550-600 for the sampling kit to help cover testing and shipping costs. Kits have been used to test seawater as far away as the Northern hemisphere's west coast.

What Are the Benefits and Challenges?

A primary benefit of citizen science is the vast amount of data collected and interpreted by volunteers, at a scale unimaginable for traditional research programs. Another primary benefit is citizen engagement, collaboration, and an increased sense of environmental awareness and responsibility. The chair of the Citizen Science Association has combined these two in identifying collective intelligence as a key benefit, with opportunities for improved decision making related to the science and goals of these collaborative projects [33]. Citizen contributions to scientific knowledge have informed countless programs. The great potential for scientific discovery is illustrated by two examples. The first is space archaeology research led by 2016 TED Prize winner Sarah Parcak at the University of Alabama at Birmingham. Dr. Parcak searches satellite images for clues about past civilizations and has identified 17 potential pyramid sites, 1,000 tombs, and several thousand unknown settlements in Egypt alone. With the $1 million TED Prize, she is establishing a citizen science website to invite "global explorers" to help scan satellite images looking for structures as well as signs of looting, to create a new global alarm system that can help protect and preserve these sites [34].

The second example is the Planet Hunters project, one of 42 in Zooniverse (https://www.zooniverse.org/projects). In this project, volunteers helped analyze four years of data from 150,000 stars, using images from NASA's telescope during the Kepler Mission search for planets like Earth. More than 300,000 citizen scientists helped scan 2.5 billion data points, and their eyes found anomalies missed by NASA's data processing algorithms. Volunteers helped discover nearly a hundred candidate exoplanets (planets orbiting a star other than ours), including several confirmed planets, and one big mystery. Light from one star in the Cygnus galaxy dipped substantially and for longer, irregular periods compared with what an orbiting planet would cause. The first paper on this discovery, led by Yale post-doctoral astrophysicist Tabetha Boyajian, suggested an irregular-shaped object more than 1,000 times bigger than Earth, a natural phenomenon not yet understood; some colleagues noted an alien technology could not be ruled out [35]. Her 2015 paper, which includes an amateur astronomer as second author, suggests the scenario might involve a family of fragments from a breakup event [36]. Amateur astronomers are collecting more data to help solve the ongoing mystery.

Many social benefits of citizen science are captured in the United Nations Environment Programme (UNEP) recent yearbook, with a chapter devoted to "realizing the potential of citizen science" [37]. Citizen science is described as "a community approach that can help put vulnerable groups on a more equal footing with other environmental stakeholders while helping to protect their resources and ultimately influencing the governance structure with respect to both their natural resources and the environment." A key opportunity provided by citizen science is "the growing capacity to involve communities and strengthen civil society while protecting the environment." Successes include citizens in Finland collaborating to restore a river ecosystem, and those in the Congo Basin mapping forests and becoming empowered to work with logging companies for forest protection. Cybertracker is also highlighted as a software program used in 700 projects across 70 countries, which relies on pictograms displayed on handheld devices to help citizens monitor water quality, invasive species, and other environmental conditions that support programs such as fire management, wildlife conservation, and more. Key benefits highlighted by UNEP [37] and others include the following.

- *Assisting agencies with limited resources* by substantially increasing spatial and temporal coverage and the total number of environmental measurements, thus increasing the statistical power of these data and their potential to provide insights into scientific questions.
- *Directly contributing to scientific knowledge*, ranging from environmental programs to new areas like drug development. (For example, gamers participating in the online protein folding game Foldit figured out the structure of an enzyme related to the human immunodeficiency virus (HIV) within 3 weeks.)
- *Providing better access to information*, including through interactive websites.
- *Bringing people together*, either directly or through social networking – including local communities, administrative authorities and policy makers. UNEP explains that when applied to natural resources management, citizen science can lead to solutions and decision-making processes that consider the viewpoints of all those concerned.

Additional benefits beyond larger data sets, scientific contributions, and increased engagement include greater awareness of and care for local environments, a sense of being a good citizen, increased personal knowledge and reputation, and environmental education, including to inspire new generations of scientists [38]. Challenges and suggested solutions identified by UNEP and others include:

- *Facilitating opportunities for participation, including tools, and training*. One way this challenge can be addressed is through ICT innovations, including online searchable databases and collaborations led by scientific institutions that can assist with training and tools. Resources range from free or inexpensive smartphone apps ($1-5) used for citizen science to inexpensive do-it-yourself kits and online toolkits and educational materials [16].
- *Improving coordination among scientists, project developers and others*. One way to address this challenge, which could help avoid confusion and redundancy, would be to have well-defined and structured project leadership, and to encourage potential new projects tap and collaborate with existing, relevant citizen science projects.
- *Sustaining participation*. This challenge could be addressed through mechanisms that sustain interest and by understanding and responding to the range of people's motivations for participating.

- *Addressing data validity*. This challenge could be addressed by having scientific communities more strongly recognize the value of data generated by citizen science through the peer-reviewed process (e.g., by including citizen scientists as authors in scientific publications, as illustrated by the Planet Hunters project and others), and to provide evidence of the quality of these data in publications (which is also being done). For example, several studies describes how data and information generated from citizen science projects have been shown to be reliable and accurate, including data processed by statistical tools that address sample bias, measurement errors or spatial clustering [37,39,40]. A further suggestion is to be clear about the purpose of the data, e.g., whether it is intended to support a screening study or provide a confirmatory check for limited data taken by professional scientists or support a quantitative analysis.
- *Expanding coordination, including internationally, to improve the aggregation and analysis of data generated by citizen scientists.* This could be addressed by communities of practice providing coordination platforms to help reveal valuable data sets useful to scientists, policymakers and others. Such communities include the Citizen Science Association, European and Australian Citizen Science Associations, and Citizen Science Alliance (with more than 250,000 members), as well as the Federal Community of Practice and OGP counterparts.

An example of expanded coordination is reflected in the recent UK progress update regarding commitments in its 2013 -2015 OGP National Action Plan [41], which discusses engagement with the public in several areas: "Sciencewise support has helped to ensure that new policies involving science and technology have benefitted from an understanding of the views and values of the public. Specific examples over the last period where the policy refers to the involvement of the public include mitochondrial transfer, *radioactive waste management, geological disposal siting process* and stratified medicine *[emphasis added]* .... Sciencewise continues to work with the departments and the stakeholders involved to investigate ways to engage with the public and to create a space for the public views and values to be considered as government develops its thinking and policy on the complex cross-departmental issues of data and regulation."

Funding can also be a constraint for certain projects, including those requiring more sophisticated sensors (such as radiation detectors). Various mechanisms exist to address this challenge. For example, some crowdsource funding through Kickstarter (like Safecast) or seek other sponsors. For many field projects, the lead organization provides nominal support, such as loaning citizens the materials they need to map urban forests during those campaigns. Simpler projects require only a laptop or desktop and internet access. For example, "digital volunteers" recently helped the Smithsonian Institution construct an electronic database of all the items stowed on the spacecraft astronauts took to the moon, Apollos 11 through 17 [42]. Traditional approaches are illustrated by agencies like NSF, which held a "Be a (citizen) scientist!" celebration in September 2015 [43], highlighting projects that had received combined NSF funding of more than $5.6 million, including: middleware for volunteer computing; protein design through massively distributed video games;

RAPID, empowering the citizen scientist in the fight against Ebola viruses; eBird, maintaining the cyberinfrastructure to support the collection, storage, archive, analysis, and access to a global biodiversity data resource; the CoCoRaHS Network, enhancements to increase participation for tens of thousands in an important nationwide climate-literacy project; and community-based rain and hail studies, practical geoscience education for all ages.

Open innovation competitions or ideation challenges are another means of engaging citizen scientists from the local to the global scale. People from different backgrounds and ages self-assemble to address a given problem. A local effort is illustrated by the Mass EduData Challenge, in which people of different backgrounds and ages self-assembled to work on frameworks for analyzing, understanding, and creatively using local data. This Challenge was hailed as building civic involvement with government, encouraging experimentation, and promoting collaboration within governments [21]. Other competitions target specific audiences to enhance science, technology, engineering, and math (STEM) education, such as the Exploration Design Challenge cosponsored by NASA, the National Institute of Aerospace, and Lockheed Martin. This challenge invited high school students to develop devices for protecting astronauts from cosmic radiation during future space flight for the Path to Mars program [44]. At the other end of the spectrum is the Tricorder X, a global competition with a grand prize of $10M for development of a portable device that can diagnose a set of medical conditions ranging from hypertension to melanoma. Hundreds of teams from around the world were reduced to a set of ten finalists – including a team led by Johns Hopkins University students. Each team is currently prototyping their device, and the winner is to be announced in early 2017 [45].

Future opportunities for citizen science include a growing population of potential volunteers as baby boomers retire, and online educational resources including from SciStarter, universities, and the Public Broadcast System Nova Labs. Meanwhile, technology advances pose both opportunities and challenges; e.g., drones can take observations over a wide geographic area yet also raise privacy and safety issues. With regard to new applications, consider evaluations conducted as part of planning for new projects, which involve baselining environmental conditions for weather, surface water, groundwater, soil, ecological resources, and visual resources. Citizen scientists have long contributed these types of data for various purposes, so the opportunity exists for such contributions to be part of future programs. An evaluation of success factors for citizen science projects suggests five aspects to consider for new initiatives: (1) volunteer demographics, with native community members having valuable indigenous knowledge; (2) community integration, with potential for enhancing environmental literacy and social and ecological resilience; (3) training opportunities, with in-person involvement corresponding to higher volunteer retention rates; (4) potential partnerships, such as with academia, laboratories, and agencies; and (5) data sharing, including considering different levels of data quality corresponding to specific program needs [46].

CONCLUSIONS

Millions of volunteers participate in citizen science, with the trend projected to continue with further ICT advances. Contributions to scientific knowledge have benefited hundreds of environmental programs, including from the collection and evaluation of baseline data for specific locations and further monitoring over time. In addition to its well-established scientific benefits, citizen science could also provide a novel opportunity for building trust and confidence among the implementing organization, key stakeholders, and the broad public in a consent-based siting process. It must be recognized that a consent-based siting process has not yet been developed for the facilities needed to manage SNF and HLW from commercial reactors in the United States, as DOE is currently seeking inputs to design such a process. Given that the process will not be defined or implemented for some time, this early exploration and example citizen science activities noted herein should not be viewed as indicating a path forward in any way; instead, these examples simply illustrate the potential opportunity citizen science might offer in the future as the process unfolds. That is, this paper should not be misinterpreted as suggesting that citizen science be applied to consent-based siting of nuclear waste management facilities. Rather, the intent is to introduce the concept into the discussion as efforts get under way to define a fair and effective consent-based siting process.

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